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THERMAL TECHNOLOGY LAB INC BUFFALO N Y  
DEVELOPMENT OF LIGHTWEIGHT TRANSFORMERS FOR AIRBORNE HIGH POWER--ETC(U)  
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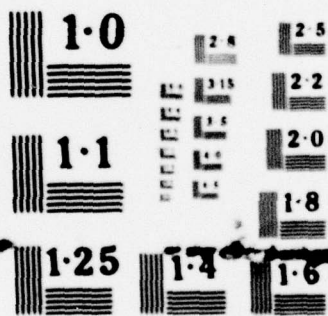
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**DEVELOPMENT OF LIGHTWEIGHT TRANSFORMERS  
FOR AIRBORNE POWER SUPPLIES**

**James P. Welsh**

**Thermal Technology Laboratory, Inc.  
422 Niagare Falls Blvd.  
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**JUNE 1979**

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**Final Report**

**July 1976 - March 1979**

**Approved for public release; distribution unlimited.**

**AIR FORCE AERO PROPULSION LABORATORY  
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433**

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## PREFACE

This final report was submitted by Thermal Technology Laboratory, Inc., under Contract F33615-75-C-2014. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project 3145, Task 32, and Work Unit 05 with Mr. Michael P. Dougherty, APAPL/POD-1 as project engineer. Mr. James P. Welsh, of Thermal Technology Laboratory, Inc. was technically responsible for the work.

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## TABLE OF CONTENTS

SECTION	Page
I - SUMMARY	1
II - INTRODUCTION	3
2.1 General	3
2.2 Transformer Design	4
2.3 Cooling Techniques	5
2.4 Specific Compromises	6
2.5 Duty Cycle Considerations	7
2.6 Safety and Reliability	7
2.7 Terminal and Bushing Considerations	8
III - TECHNICAL DISCUSSION	9
3.1 Introduction	9
3.2 10 KVA Inverter Transformers	9
3.2.1 10 KW Water Cooled Transformer Rectifier System	9
3.2.2 10 KW Air Cooled Transformer Rectifier System	11
3.3.3 Transformer Impedance	19
3.2.4 10 KW Inverter Tests	23
3.3 200 KW Inverter Transformers	25
3.3.1 General	25
3.3.2 200 KW T/R Unit No.1	28
3.3.3 200 KW T/R System No.2	32
3.3.3.1 Modified Design	32
3.3.3.2 Final Design	39
3.3.4 200 KW T/R Unit Heat Transfer System Design	44
3.3.4.1 Pie Windings	44
3.3.4.2 Diodes	45
3.3.4.3 Core	45
3.3.4.4 Condensation Process	45
3.3.4.5 Water Cooled Cover	47
3.3.4.6 Temperature Limitations	47
3.3.4.7 Temperature Rise Summary	47
3.3.5 200 KW T/R Unit	50
3.3.6 200 KW Resistive Load	50
IV - CONCLUSIONS	53
APPENDIX A - Non-Iterative Design Program	55
APPENDIX B - HP-9830 Computer Programs	59
REFERENCES	62

# LIST OF ILLUSTRATIONS

FIGURE		Page
1	Water Cooled Transformer Enclosure	10
2	10 KVA Transformer	12
3	10 KVA Inverter Transformer	13
4	10 KVA Transformer Design Data	14
5	Preliminary Design 10 KVA Transformer	15
6	Design Data-Preliminary Design	16
7	Compact Preliminary Design	17
8	Compact Preliminary Design Data	18
9	Final Design 10 KVA Transformer	20
10	Final Design Data 10 KVA Transformer	21
11	Air Cooled 10 KW T/R Unit	22
12	Inverter Waveforms	24
13	Pie mounted diode bridge configuration	27
14	200 KVA Transformer	29
15	Detailed View - 200 KVA Transformer	30
16	Detailed Listing-200 KVA Transformer	31
17	Final Design - 200 KVA Transformer	33
18	Final Design- 200 KVA Transformer	34
19	Detailed Listing-Final Design-200 KVA Transformer	35
20	CAD Output Listing 200 KVA Transformer No.2	36
21	Winding Configuration-200 KVA Transformer No.2	37
22	KVA T/R Unit No.2	38
23	Modified Design Program - 200 KVA T/R Unit No. 2	40
24	Design Parameters - Modified Program	43
25	Condensate to Cover vs Fin Length	48
26	Temperature Diff.-Cover to Coolant vs Flow Rate	49
27	200 KW T/R Unit	51
28	200 KW Load Bank System	52

## SECTION I

### SUMMARY

This document reports on the conclusion of work conducted under contract number F33615-75-C-2014, during the period of July 1976 through March 1979. Previous work is reported in the Interim Report, number AFAPL-TR-76-102. For a complete description of all work performed in the overall program, both this report and the Interim Report must be used in conjunction.

The emphasis on this program was on the development of high voltage, high power, low specific weight, inverter transformers. A primary goal of the program was the reduction of the specific weight of inverter transformers without sacrifice of either electrical performance or reliability. Research was conducted into the characteristics of magnetic and dielectric materials, improved magnetic circuit modeling and application of advanced heat transfer techniques. The program has been successfully concluded and two basic transformer rectifier (T/R) unit designs (10 Kw and 200 Kw) were fabricated and demonstrated.

One of the goals of the program, to achieve a specific weight of 0.25 lbs/KVA, was exceeded. A specific weight of approximately 0.10 lb/KVA was actually accomplished with the 200 KVA transformer. The total measured weight, with rectifiers included, resulted in a specific weight of about 0.13 lb/KVA. It is predicted that in larger sizes, specific weights in the order of 0.07 lb/KVA can be realized.

The inverter transformers developed in this program exhibited unusually low leakage inductances and high efficiencies. They should also provide higher reliability than conventional transformers due to much lower operating temperatures (ie: lower thermal stress) on the conductors and insulation. In addition, the transformers can absorb severe overloads without damage and without damaging adjacent hardware. This is due to the capability of the vaporization cooling technique to safely dissipate large amounts of power.

All of the primary efforts of this program have been successfully accomplished:

- A 10 KVA inverter transformer was designed, fabricated and tested.
- Two 10 KVA transformer/rectifier (T/R) units (one liquid-cooled version and one air-cooled version) were fabricated and delivered.
- Research was conducted into the characteristics of magnetic and dielectric materials, improved magnetic circuit modeling, and application of advanced heat transfer techniques.
- Computer-aided design methods were utilized and specialized programs developed to permit extensive manipulation of multiple design parameters.
- An experimental 200 KVA inverter transformer was designed.
- Two 200 KVA T/R units were developed, fabricated, subjected to preliminary testing and delivered. (Full load testing awaits delivery of a 200 KW inverter. An addendum report will be issued after completion of the full load tests.)
- A high voltage non-inductive load suitable for testing the above T/R units was designed, fabricated, tested and delivered.

In addition, the measured performance of both the 10 KW and 200 KW units verified the computer aided design program predictions, thus successfully establishing the validity of the programs.

## SECTION II

### INTRODUCTION

#### 2.1 General

The increasing requirements for aircraft performance, size, and electronic systems capabilities has placed electrical power demands on future power conditioning equipment which can no longer be effectively handled by existing hardware and the related technology. Pertinent to this program was the requirement for small lightweight high power magnetics having specific weights in the range of  $\frac{1}{4}$  lb. per KVA at 400 HZ and higher. The USAF Aero Propulsion Lab., at Wright-Patterson AF Base, has sponsored the R&D reported herein with the primary goal of reducing the specific weight of magnetics without sacrificing electrical performance and reliability. Emphasis has been on power, inverter, and pulse transformers. Emphasis on this contract however, was on inverter transformers only.

Transformers with specific weights in the range of 0.1 to 0.25 lbs/KVA have been successfully developed during this program by TTL. The utilization of improved materials, improved magnetic circuit modeling, and the application of advanced heat transfer techniques has resulted in this breakthrough. The thermal aspects are particularly important to the size and weight reduction of magnetics. If each conductor in a magnetic device can be adequately cooled throughout most of its length, then the current density can be increased and the conductor crosssectional area significantly reduced. This, in turn, results in a smaller core window and consequently, a smaller core.

It was initially established on the previous TTL contract-F33615-72-C-1944, that the power, size, and weight limiting condition in transformers is the rate at which heat can be removed from the windings, and to a lesser extent, the magnetic cores. Thus, one of the basic approaches in this research was to emphasize internal heat transfer in transformers and to develop thermal techniques that could provide the lowest practical thermal resistances. This permitted conductor current densities which were almost an order of magnitude greater than those in conventional transformers.

The main thrust of the program has been to utilize modern computing techniques, advanced magnetics analyses and modeling, and thermal technology backed by extensive experimentation to develop lightweight transformer design procedures. Various experimental transformers were designed, constructed and tested to demonstrate the validity of this approach.

The selection of suitable magnetic and insulating materials has been addressed in this program. The highlights of thermal analysis and experimentation to evolve controlled cooling of conductors were previously reported. Electrical design, magnetic models, and the resultant computer aided design programs were developed in this contract. This enables a designer to rapidly study the effects of changes in materials, geometry, and many other physical parameters.

Lightweight Transformer/Rectifier Units at power levels of 10 Kw and 200 Kw were designed and fabricated to demonstrate the new lightweight technology developed under this contract. Their performance was very consistent with the computer predictions and validated the programs.

## 2.2 Transformer Design

Two approaches to transformer design were developed. The first approach, which has been called the steady state analysis routine, is basically a magnetic circuit approach. This method uses flux and flux leakage concepts to relate the primary and secondary in a transformer. The second approach, which has been called the real time analysis routine, is a coupled electric circuit approach in which the primary and secondary are related through their inductances. This has been reported in Interim Report AFAPL-TR-76-102.

In formulating the governing equations for transformer design, it was found that the mathematics of steady state design are not especially complex, but that the design process is complicated by the profusion of design input variables. Depending upon the application, between fifty and two hundred

parameters, all interrelated by physical laws and performance criteria, are required to fully describe a design. Since many of the relationships are not only non-linear, but are discontinuous, the manipulation of these parameters to achieve optimum results becomes formidable. However, a programmable calculator can be used for parametric analyses and design, provided a complete design optimization is not desired. Complex optimization programs for large machines were also developed and delivered to the USAF.

### 2.3 Cooling Techniques

Since vaporization cooling techniques were determined very early in the previous program to be most applicable to the high heat fluxes anticipated, much of the thermal investigation and experimentation was directed to the application of this cooling method. While a considerable amount of literature exists on the boiling process, much of it is empirical in nature and therefore limited in scope, and little if any is directly applicable to the problem of boiling in narrow vertical ducts as are found in the transformer. The analyses and experiments were directed at obtaining values of the maximum attainable heat flux without exceeding the nucleate boiling regime, and of the minimum channel width required to insure against the formation of vapor pockets with the attendant extreme temperature rises and potential burnout. Other cooling techniques such as direct liquid cooling and forced liquid cooling are also applicable to cooling the lightweight transformers, dependent upon conductor current density (ie: heat flux).

Vaporization and liquid cooling application additionally led to other considerations. Computability tests indicated that testing of the materials involved is desirable for a given application with a specific coolant. The high electric fields and small spacings typical of reduced size transformers require detailed knowledge of dielectric breakdown, particularly in view of the two phase nature of the dielectric coolant. Dielectric breakdown and insulation relationships and models were refined and experimentally validated for use in this

program. Also, the open construction required to provide coolant passages resulted in consideration of the mechanical forces imposed on the windings, especially under overload conditions.

#### 2.4 Specific Compromises

Reduction in weight and size is not always without a penalty. This penalty is often (but not always) reduced efficiency. The efficiency of well designed conventional high power transformers is usually in the neighborhood of 98 to 99.5 percent. The low specific weight transformers tend to exhibit 2 to 4 percent lower efficiency. This is a small penalty and often can be easily accommodated when an external cooling system is provided. This however, does not mean that low specific weight transformers of the same efficiency as conventional transformers cannot be built; they can be, but are somewhat larger and heavier than lower efficiency units. Users tend to prefer the lower specific weight transformer and accept the lower efficiency in order to realize a lower overall system weight. Another penalty is a slightly degraded voltage regulation due to the increased conductor resistances in the windings of low specific weight transformers. Usually, these are small compared to the external system resistances and are offset by the relatively small increase in resistance due to much lower winding temperature rises in the low specific weight transformers. Further, the low specific weight transformers have shorter total conductor lengths in a given winding compared to conventional transformers, which also tends to offset the slightly degraded voltage regulation. The computer programs developed permit the tradeoff of transformer gains and penalties such as weight, size, efficiency, voltage regulation leakage inductance, and many other parameters with respect to any given set of transformer requirements.

## 2.5 Duty Cycle Considerations

The transformers developed under this program are mostly continuous duty transformers. The time required for the windings to reach thermal equilibrium in a thermally adequate design is very short, much shorter than any contemplated duty cycle. Thus, from the viewpoint of the internal thermal aspects, the transformers are capable of continuous duty. However, for intermittent duty applications, the external cooling system can be reduced in size, weight, and capability to accommodate the specific duty cycle desired. Thus, a lightweight transformer system capable of any required duty cycle can be designed and developed.

There is another class of lightweight transformer which also can be designed - namely the "adiabatic transformer". These are transformers which are intended for very short duty application and incorporate relatively high internal thermal resistances. The duty cycle is limited by the total quantity of heat the transformer materials can absorb without attaining excessive temperatures. The transformer must "cool down" prior to reenergization.

## 2.6 Safety and Reliability

The small lightweight high power transformers developed can withstand considerable overload in spite of their small size. For example the two hundred KVA transformer has a volume of about 300 Cu. in. When this transformer is connected to power sources capable of several megawatts, it initially looks like a "bomb" if an internal fault occurs. However, because vaporization cooling is used, the coolant is capable of safely dissipating very large powers. Further, the operating temperatures of the transformers are lower than with conventional transformers. The overall reliability should equal or exceed that presently attained because the electrical, thermal and mechanical stresses on the materials are carefully controlled design parameters.

## 2.7 Terminal and Bushing Considerations

One problem common to these transformers is that of providing adequate input and output terminals and bushings. The large currents and/or voltages involved mandate large conductors or bushings with long leakage paths which are generally incompatible with the small sizes of the transformers. For example, with the 200 KW units, the input currents at 10 KHZ are greater than 400 amps and a low inductance is also required. The terminals and bushings can therefore constitute a significant portion of the volume and weight of a low specific weight transformer.

## SECTION III

### TECHNICAL DISCUSSION

#### 3.1 Introduction

During the development of the 10 KVA experimental inverter transformer, new techniques for fabrication of pie wound transformers were developed which yielded superior designs. As described in the interim report (AFAPL-TR-76-102), dated December 1976, this development was followed by the development of computer aided design programs for pie wound transformers. Several 10 KVA transformers were fabricated and subjected to a variety of tests. Based on the results of these tests, both the final 10 KVA and the 200 KVA transformers are pie wound. As a preliminary step toward the design and fabrication of the final 10 KW transformer rectifier system, a 10 KW water cooled transformer rectifier unit was designed and fabricated.

#### 3.2 10 KVA Inverter Transformers

##### 3.2.1 10 KW Water Cooled Transformer Rectifier System

The 10 KW water cooled transformer design was based on the third version of the computer aided "pie wound" design program. The primary winding is of edge wound rectangular (Approx. 0.125" x 0.05") copper strip, which is mounted on a "Mylar" insulator disk (Approx. 2½" Dia. x 1/32" Thk.). The #30 AWG secondary windings are mounted on the other side of the insulator disk and dimensioned so as to match the primary dimensions. This configuration minimizes leakage inductance and provides excellent strength. The tape-wound core is a double-C configuration and is made with 1 mil thick Orthonol. Each section has external dimensions of approximately 2½" x 2" x 3/4" and is wound to about ½" thickness. This transformer is capable of operation well above 10 KW. The estimated maximum capability is about 60 KVA.

The prototype water cooled enclosure for the transformer rectifier system was machined out of a single aluminum block with internal condensing fins. The transformer and rectifiers are mounted on a transparent acrylic base plate with all feed throughs brought out of the bottom. The completed enclosure is shown, approximately full size, in Fig. 1. It should be noted that this enclosure configuration is experimental only; For an operational situation, the enclosure would be different (ie: thinner wall, Etc.).

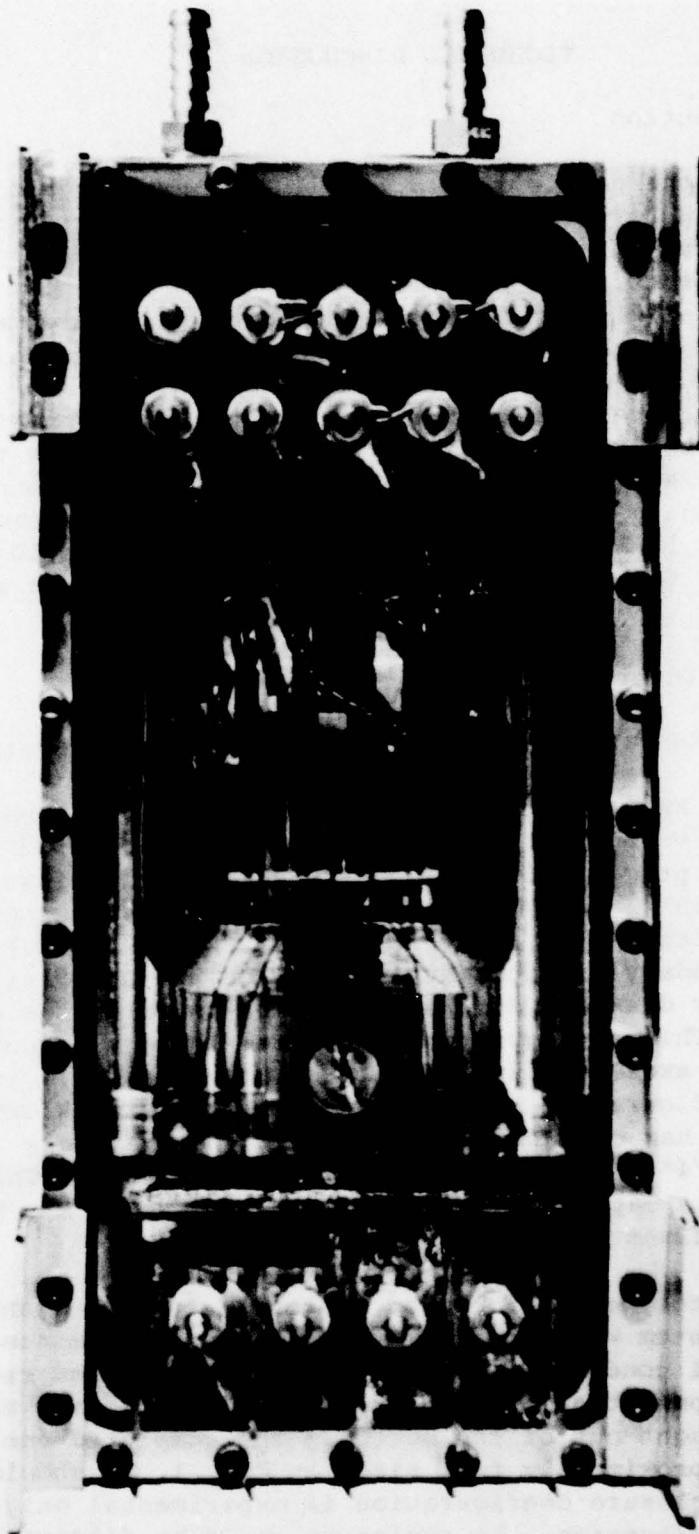


Figure 1. Water Cooled Transformer Enclosure (Bottom View)

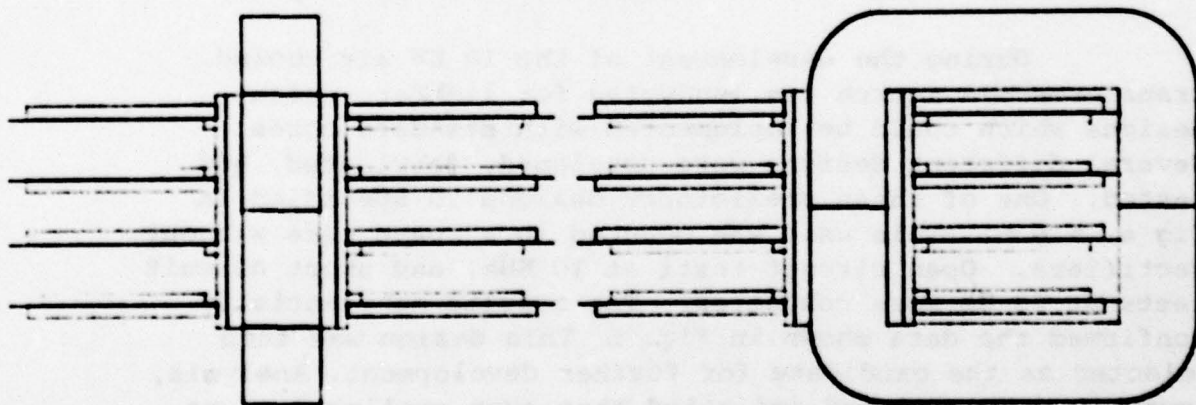
The transformer rectifier unit was completed and tested in Dec. 1976. It weighed less than 2 lbs. (excluding case and coolant), for a specific weight of less than 0.2 lbs/KVA. It was driven at 10 KHz by an inverter operating from 500 V. DC, and delivered 9200 volts at 1.1 A, to the load. The overall inverter system efficiency was 89%.

During the later design stages of the water cooled transformer, the interactive pie wound transformer design program was modified to include a plot routine which provides a scaled drawing of the transformer. A typical single-C core design is shown in Fig. 2.

Also, further study of the pie wound design programs disclosed that the thermal conditions imposed on the transformer coils are sufficient to predetermine the transformer efficiency. Thus, the iteration routine is not required. A new non-iterative program was written for pie wound transformers. An additional variation was added which permits the incorporation of flat primary windings. Finally, to minimize leakage inductance, the program requires that there are the same number of primary and secondary coils and that their inside and outside diameters exactly match. It should be noted that the water cooled inverter transformer was fabricated with all of the above changes. A drawing of the transformer is shown in Fig. 3. This design conforms exactly to the actual hardware. The complete data are tabulated in Fig. 4. A listing of the pie wound design program is presented in Appendix A.

### 3.2.2 10 KW Air Cooled Transformer Rectifier System

During the development of the 10 KW air cooled transformer, a search was conducted for lighter weight designs which could be implemented with standard cores. Several different designs were developed, fabricated, and tested. One of these preliminary designs is specified in Figs. 5 & 6. This unit was mounted in a spare case without rectifiers. Open circuit tests at 10 KHz, and short circuit tests at 60 Hz were conducted. The results substantially confirmed the data shown in Fig. 6. This design was then selected as the candidate for further development. Analysis, however, continued and indicated that even smaller designs were possible with more standard cores becoming available. The smallest overall design developed on the computer is shown in Fig. 7. The complete data are tabulated in Fig. 8.



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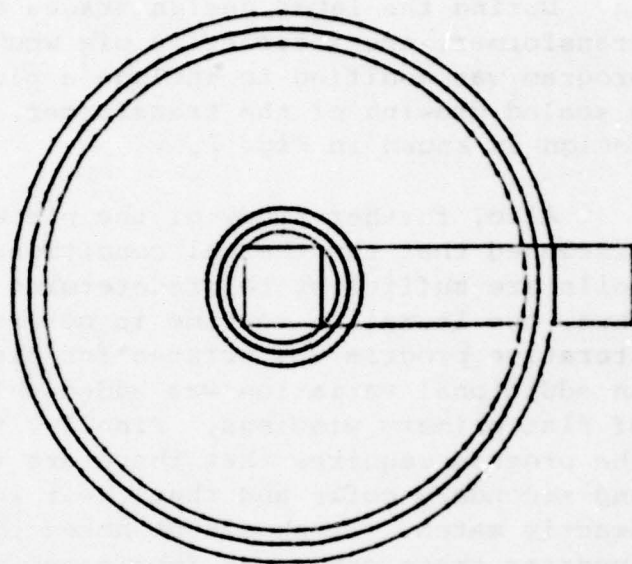
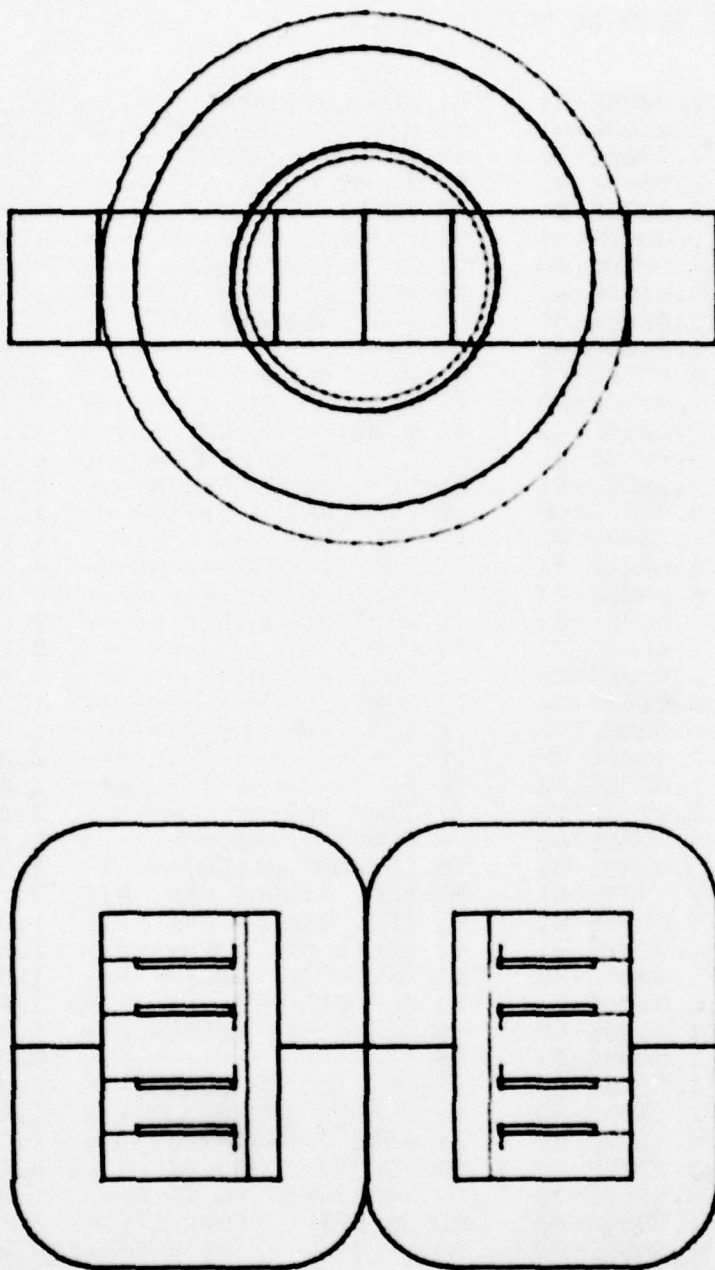


Figure 2 - 10 KVA Transformer



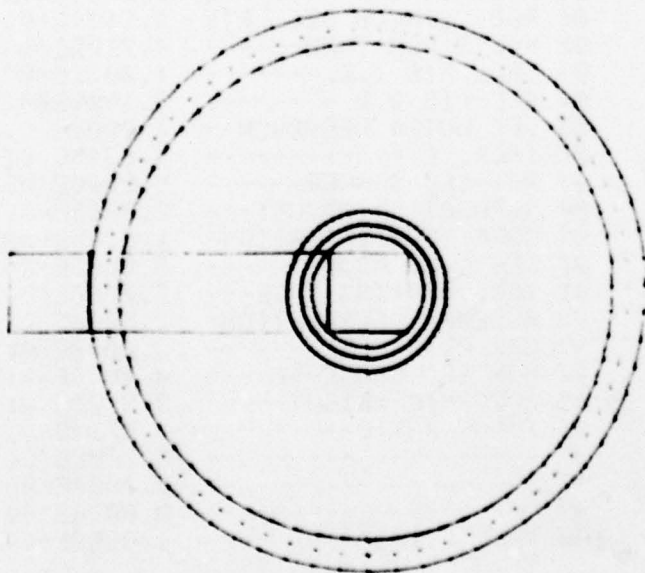
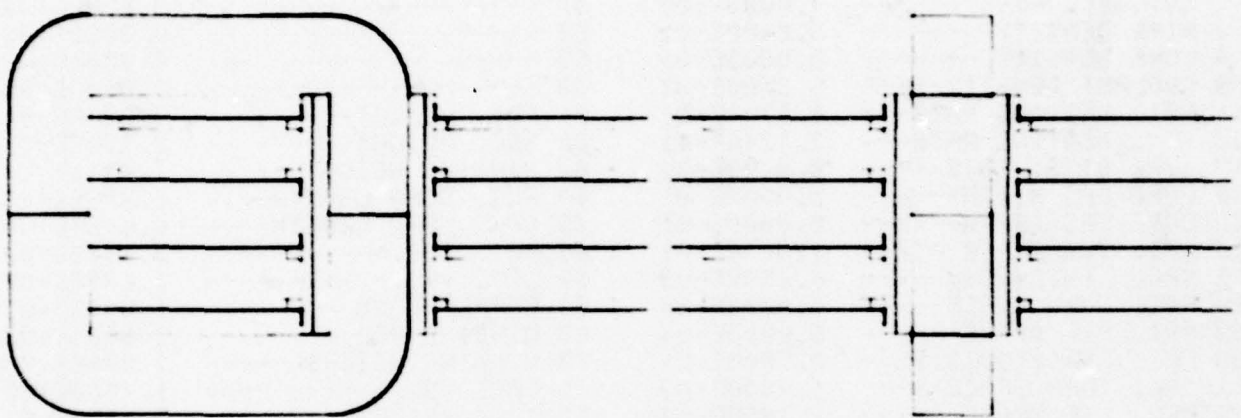
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Figure 3. 10 Kw Inverter Transformer (105 C; MC 1391 Core)

## 10 KW INVERTER TRANSFORMER (105 C; NC1391 CORE)

1	OUTPUT VOLTAGE-----	1.0000E+04	51	REGULATION-----	4.3523E-03
2	INPUT VOLTAGE-----	2.8500E+02	52	MIN COOLING SPACE---	1.0000E-02
3	WIRE RESISTIVITY----	6.7800E-07	53	OUTPUT CURRENT-----	1.0000E+00
4	CORE STACKING FACTOR--	8.5000E-01	54	INPUT POWER-----	1.0171E+04
5	FLUX DENSITY-----	5.0000E+04	55	INPUT CURRENT-----	3.5686E+01
6	FREQUENCY-----	1.0000E+04	56	PRIMARY LOSS-----	1.4093E+00
7	NO. PIES-----	4.0000E+00	57	SECONDARY LOSS-----	4.2279E+01
8	WIRE DENSITY-----	3.2400E-01	58	SEC LOSS PER PIE----	1.0570E+01
9	CORE DENSITY-----	3.0200E-01	59	PRI LOSS PER PIE----	3.5232E-01
10	COOLANT DENSITY-----	5.6500E-02	60	-----	0.0000E+00
11	-----	0.0000E+00	61	PRI. HEIGHT-----	2.9800E-01
12	-----	0.0000E+00	62	SEC. HEIGHT-----	1.6483E-01
13	CORE DISS. RATE-----	8.0000E+01	63	WINDING HEIGHT-----	1.1827E+00
14	CORE LEG WIDTH-----	5.0000E-01	64	PRI. MEAN LENGTH-----	6.4528E+00
15	CORE LEG DEPTH-----	7.5000E-01	65	SEC. MEAN LENGTH-----	6.4528E+00
16	PRI. TURNS PER PIE--	5.0337E+00	66	PRI. RES.-----	1.1066E-03
17	SPOOL THICKNESS-----	6.6500E-02	67	SEC. RES.-----	4.2279E+01
18	PRI. TURN SPACE-----	6.0000E-04	68	COPPER LOSS-----	4.3688E+01
19	PRI. PIE SPACE-----	6.0000E-04	69	WINDING VOL.-----	8.8450E-01
20	PRI. SPACE OUTSIDE--	2.5000E-02	70	WINDING WEIGHT-----	2.8650E-01
21	SEC. TURN SPACE-----	1.4000E-03	71	CORE VOL.-----	5.2500E+00
22	-----	0.0000E+00	72	CORE WEIGHT-----	1.5055E+00
23	-----	0.0000E+00	73	CORE LOSS-----	1.2674E+02
24	-----	0.0000E+00	74	TOT. PWR. LOSS-----	1.7053E+02
25	BREAKDOWN FACTOR-----	2.0000E-05	75	-----	0.0000E+00
26	CORE FORM FACTOR-----	2.0000E+00	76	-----	0.0000E+00
27	COIL SURFACE AREA---	3.5232E+00	77	TANK VOL.-----	3.0000E-01
28	PWR. INCR.-----	5.0000E+02	78	COOLANT VOL.-----	2.3866E+01
29	SEC INNER KEEPBACK--	5.0000E-02	79	COOLANT WEIGHT-----	1.3484E+00
30	PRI. WIDTH-----	2.1574E-01	80	RES. SINGLE PRI. PIE	2.7666E-04
31	SEC. WIRE GAUGE-----	3.0000E+01	81	RES. SINGLE SEC. PIE	1.0570E+01
32	MAX PRI. HEAT TRANS.	1.0000E-01	82	VOLTS PER TURN-----	1.4153E+01
33	MAX SEC. HEAT TRANS.	3.0000E+00	83	SEC. PIE I.D.-----	1.5000E+00
34	NO. PARALLEL SECS.--	1.0000E+00	84	SEC-PIE O.D.-----	2.6000E+00
35	NO. PARALLEL PRIS.--	1.0000E+00	85	SEC OUTER KEEPBACK--	2.0000E-01
36	MAX PWR. OUTPUT-----	1.0000E+04	86	-----	0.0000E+00
37	PRI. I.D.-----	1.5080E+00	87	PRI-SEC SPACER-----	5.0000E-03
38	PRI. O.D.-----	2.6000E+00	88	SEPARATION ADJUST---	2.0000E-01
39	THICKNESS SEC. PIE--	4.1208E-02	89	CORE IDENTIFICATION--	1.3910E+03
40	PRI. THICKNESS-----	7.3301E-02	90	SEC O.D. ADJUST-----	0.0000E+00
41	SEC. WIRE DIA.-----	9.6690E-03	91	TOT. HEATING RATE---	1.0922E+01
42	WINDOW WIDTH-----	1.0000E+00	92	ASSEMBLY SEPARATION--	2.1662E-01
43	WINDOW HEIGHT-----	1.5000E+00	93	-----	0.0000E+00
44	PRI. TURNS-----	2.0135E+01	94	-----	0.0000E+00
45	SEC. TURNS-----	7.0958E+02	95	SPECIFIC WEIGHT-----	3.2205E-01
46	SPOOL O.D.-----	1.3830E+00	96	TURNS RATIO-----	3.5241E+01
47	SEC. TURNS PER PIE--	1.7739E+02	97	-----	0.0000E+00
48	SEC I.D. ADJUST-----	2.5000E-02	98	-----	0.0000E+00
49	EFFICIENCY-----	9.8323E-01	99	-----	0.0000E+00
50	TOT. WEIGHT-----	3.2205E+00	100	PWR. OUTPUT-----	1.0000E+04

Figure 4. 10 KVA Transformer Design Data



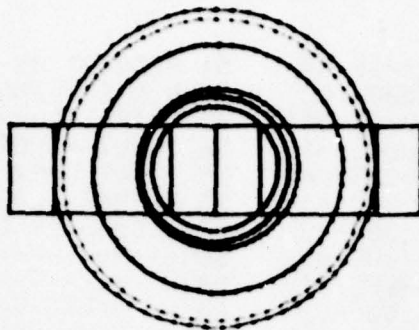
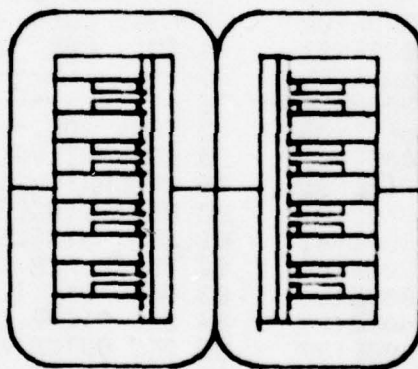
Scale 1:1

Figure 5 - Preliminary Design - 10 KVA Transformer

## DATA FILE # 24

1	OUTPUT VOLTAGE-----	1.0000E+04	51	REGULATION-----	1.8093E-02
2	INPUT VOLTAGE-----	2.8500E+02	52	MIN COOLING SPACE---	1.0000E-02
3	WIRE RESISTIVITY----	6.7800E-07	53	OUTPUT CURRENT-----	1.0000E+00
4	CORE STACKING FACTOR	8.5000E-01	54	INPUT POWER-----	1.0168E+04
5	FLUX DENSITY-----	5.0000E+04	55	INPUT CURRENT-----	3.5678E+01
6	FREQUENCY-----	1.0000E+04	56	-----	0.0000E+00
7	NO. SEC. PIES-----	4.0000E+00	57	-----	0.0000E+00
8	WIRE DENSITY-----	3.2400E-01	58	-----	0.0000E+00
9	CORE DENSITY-----	3.0200E-01	59	-----	0.0000E+00
10	COOLANT DENSITY-----	5.6500E-02	60	-----	0.0000E+00
11	PRI. HEATING RATE---	6.6304E-01	61	PRI. HEIGHT-----	3.2800E-01
12	SEC. HEATING RATE---	2.7246E-01	62	SEC. HEIGHT-----	2.7307E-01
13	CORE DISS. RATE-----	8.0000E+01	63	WINDING HEIGHT-----	1.4211E+00
14	CORE LEG WIDTH-----	5.0000E-01	64	PRI. MEAN LENGTH----	6.4786E+00
15	CORE LEG DEPTH-----	5.0000E-01	65	SEC. MEAN LENGTH----	6.4484E+00
16	PRI. TURNS PER PIE--	1.5006E+01	66	PRI. RES.-----	5.1418E-02
17	SPOOL THICKNESS-----	6.6500E-02	67	SEC. RES.-----	1.1873E+02
18	PRI. TURN SPACE-----	6.0000E-04	68	COPPER LOSS-----	1.8418E+02
19	PRI. PIE SPACE-----	6.0000E-04	69	WINDING VOL.-----	3.0865E+00
20	PRI. SPACE OUTSIDE--	2.5000E-02	70	WINDING WEIGHT-----	1.0000E+00
21	SEC. TURN SPACE-----	1.4000E-03	71	CORE VOL.-----	1.7500E+00
22	SEC. PIE SPACE-----	1.1000E-03	72	CORE WEIGHT-----	5.2850E-01
23	SEC. SPACE OUTSIDE--	0.0000E+00	73	CORE LOSS-----	4.2280E+01
24	EFF. INCR.-----	1.0000E-02	74	TOT. PWR. LOSS-----	2.2646E+02
25	BREAKDOWN FACTOR----	2.0000E-05	75	-----	0.0000E+00
26	-----	0.0000E+00	76	-----	0.0000E+00
27	-----	0.0000E+00	77	TANK VOL.-----	2.8000E+01
28	PWR. INCR.-----	5.0000E+02	78	COOLANT VOL.-----	2.3163E+01
29	SEC INNER KEEPBACK--	7.0057E-02	79	COOLANT WEIGHT-----	1.3087E+00
30	PRI. WIRE GAUGE-----	1.2000E+01	80	RES. SINGLE PRI. PIE	1.2855E-02
31	SEC. WIRE GAUGE-----	3.0000E+01	81	RES. SINGLE SEC. PIE	2.9681E+01
32	MAX PRI. HEAT TRANS.	1.0000E+00	82	VOLTS PER TURN-----	4.7175E+00
33	MAX SEC. HEAT TRANS.	5.0000E-01	83	SEC. PIE I.D.-----	1.0052E+00
34	-----	0.0000E+00	84	SEC-PIE O.D.-----	3.1000E+00
35	-----	0.0000E+00	85	SEC OUTER KEEPBACK--	2.0000E-01
36	MAX PWR. OUTPUT-----	1.0000E+04	86	INCR. EFF.-----	9.8345E-01
37	PRI. I.D.-----	8.4011E-01	87	PRI-SEC SPACER-----	5.0000E-03
38	PRI. O.D.-----	3.2843E+00	88	SEPARATION ADJUST---	2.0000E-01
39	THICKNESS SEC. PIE--	6.8267E-02	89	CORE IDENTIFICATION--	1.6100E+03
40	PRI. WIRE DIA.-----	8.0801E-02	90	SEC O.D. ADJUST-----	0.0000E+00
41	SEC. WIRE DIA.-----	1.0028E-02	91	TOT. HEATING RATE---	2.7760E+00
42	WINDOW WIDTH-----	1.5000E+00	92	ASSEMBLY SEPARATION--	2.5000E-01
43	WINDOW HEIGHT-----	1.5000E+00	93	MAX PRI GAUGE-----	2.0000E+01
44	PRI. TURNS-----	6.0025E+01	94	MAX SEC GAUGE-----	4.0000E+01
45	SEC. TURNS-----	2.1449E+03	95	SPECIFIC WEIGHT-----	2.8373E-01
46	PRI. PIES-----	4.0000E+00	96	TURNS RATIO-----	3.5734E+01
47	SEC. TURNS PER PIE--	5.3623E+02	97	-----	0.0000E+00
48	SEC I.D. ADJUST-----	2.5000E-02	98	-----	0.0000E+00
49	EFFICIENCY-----	9.7786E-01	99	-----	0.0000E+00
50	TOT. WEIGHT-----	2.8373E+00	100	PWR. OUTPUT-----	1.0000E+04

Figure 6. Design Data - Preliminary Design



EFFICIENCY 95.8%  
 WEIGHT 0.97 LB  
 FREQUENCY 10 KHZ  
 CORE ORTHONOL  
 VIN/VOUT 285/10,000

10 KW INVERTER TRANSFORMER (155 C/2-MC-1380A)

SCALE 1/1

Figure 7 - Compact Preliminary Design

DATA FILE # 30

10 KW INVERTER TRANSFORMER (155 C-2-MC-1380A)

1	OUTPUT VOLTAGE-----	1.0000E+04	51	REGULATION-----	3.9356E-02
2	INPUT VOLTAGE-----	2.8500E+02	52	MIN COOLING SPACE---	5.0000E-02
3	WIRE RESISTIVITY----	1.0000E-06	53	OUTPUT CURRENT-----	1.0000E+00
4	CORE STACKING FACTOR	8.5000E-01	54	INPUT POWER-----	1.0379E+04
5	FLUX DENSITY-----	5.0000E+04	55	INPUT CURRENT-----	3.6418E+01
6	FREQUENCY-----	1.0000E+04	56	PRIMARY LOSS-----	1.5576E+02
7	NO. SEC. PIES-----	8.0000E+00	57	SECONDARY LOSS-----	2.5347E+02
8	WIRE DENSITY-----	3.2400E-01	58	-----	0.0000E+00
9	CORE DENSITY-----	2.8088E-01	59	-----	0.0000E+00
10	COOLANT DENSITY-----	5.6500E-02	60	-----	0.0000E+00
11	PRI. HEATING RATE---	4.0952E+00	61	PRI. HEIGHT-----	3.6414E-01
12	SEC. HEATING RATE---	1.6150E+00	62	SEC. HEIGHT-----	5.2239E-01
13	CORE DISS. RATE-----	8.0000E+01	63	WINDING HEIGHT-----	1.3265E+00
14	CORE LEG WIDTH-----	2.5000E-01	64	PRI. MEAN LENGTH---	4.0034E+00
15	CORE LEG DEPTH-----	5.0000E-01	65	SEC. MEAN LENGTH---	3.6440E+00
16	PRI. TURNS PER PIE--	8.5009E+00	66	PRI. RES.-----	1.1744E-01
17	SPOOL THICKNESS-----	6.2500E-02	67	SEC. RES.-----	2.5347E+02
18	PRI. TURN SPACE-----	6.0000E-04	68	COPPER LOSS-----	4.0923E+02
19	PRI. PIE SPACE-----	6.0000E-04	69	WINDING VOL.-----	7.3073E-01
20	PRI. SPACE OUTSIDE--	2.5000E-02	70	WINDING WEIGHT-----	2.3675E-01
21	SEC. TURN SPACE-----	1.4000E-03	71	CORE VOL.-----	1.3281E+00
22	SEC. PIE SPACE-----	1.1000E-03	72	CORE WEIGHT-----	3.7304E-01
23	SEC. SPACE OUTSIDE--	0.0000E+00	73	CORE LOSS-----	2.9843E+01
24	EFF. INCR.-----	1.0000E-02	74	TOT. PWR. LOSS-----	4.3907E+02
25	BREAKDOWN FACTOR----	2.0000E-05	75	-----	0.0000E+00
26	CORE FORM FACTOR----	2.0000E+00	76	-----	0.0000E+00
27	-----	0.0000E+00	77	TANK VOL.-----	8.3828E+00
28	PWR. INCR.-----	5.0000E+02	78	COOLANT VOL.-----	6.3240E+00
29	SEC INNER KEEPBACK--	3.7615E-02	79	COOLANT WEIGHT-----	3.5730E-01
30	PRI. WIRE GAUGE-----	1.6000E+01	80	RES. SINGLE PRI. PIE	1.6777E-02
31	SEC. WIRE GAUGE-----	3.4000E+01	81	RES. SINGLE SEC. PIE	3.1684E+01
32	MAX PRI. HEAT TRANS.	5.0000E+00	82	VOLTS PER TURN-----	4.7175E+00
33	MAX SEC. HEAT TRANS.	2.0000E+00	83	SEC. PIE I.D.-----	9.0734E-01
34	-----	0.0000E+00	84	SEC-PIE O.D.-----	1.4125E+00
35	-----	0.0000E+00	85	SEC OUTER KEEPBACK--	2.0000E-01
36	MAX PWR. OUTPUT-----	1.0000E+04	86	INCR. EFF.-----	9.6346E-01
37	PRI. I.D.-----	8.3211E-01	87	PRI-SEC SPACER-----	5.0000E-03
38	PRI. O.D.-----	1.7166E+00	88	SEPARATION ADJUST---	0.0000E+00
39	THICKNESS SEC. PIE--	6.5299E-02	89	CORE IDENTIFICATION--	1.3800E+03
40	PRI. WIRE DIA.-----	5.0821E-02	90	SEC O.D. ADJUST-----	0.0000E+00
41	SEC. WIRE DIA.-----	6.3075E-03	91	TOT. HEATING RATE---	1.9770E+01
42	WINDOW WIDTH-----	6.5625E-01	92	ASSEMBLY SEPARATION--	5.0000E-02
43	WINDOW HEIGHT-----	1.5000E+00	93	MAX PRI GAUGE-----	2.0000E+01
44	PRI. TURNS-----	5.9507E+01	94	MAX SEC GAUGE-----	4.0000E+01
45	SEC. TURNS-----	2.1735E+03	95	SPECIFIC WEIGHT-----	9.6710E-02
46	PRI. PIES-----	7.0000E+00	96	TURNS RATIO-----	3.6525E+01
47	SEC. TURNS PER PIE--	2.7169E+02	97	-----	0.0000E+00
48	SEC I.D. ADJUST-----	0.0000E+00	98	-----	0.0000E+00
49	EFFICIENCY-----	9.5794E-01	99	-----	0.0000E+00
50	TOT. WEIGHT-----	9.6710E-01	100	PWR. OUTPUT-----	1.0000E+04

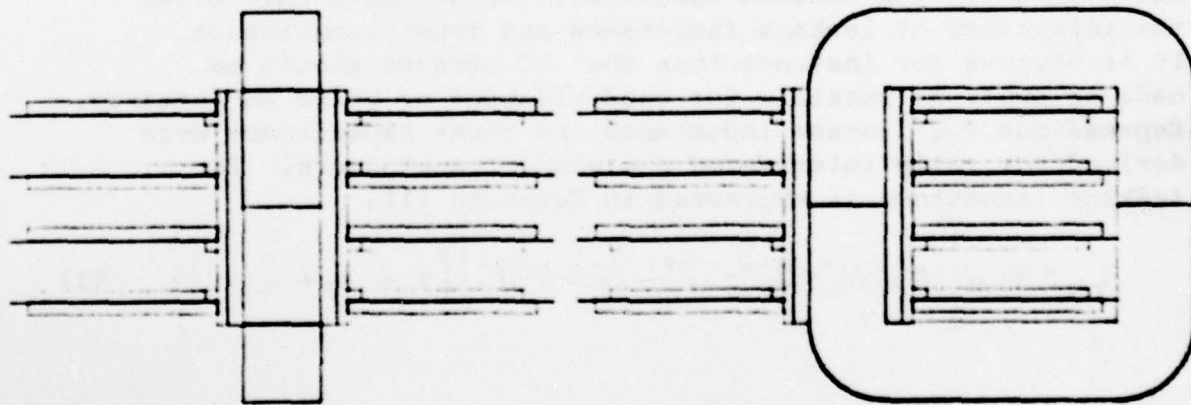
Figure 8. Compact Preliminary Design Data

The final design selected for the air cooled system incorporates a single "C" core transformer, as shown in Fig. 9 and tabulated in Fig. 10. The standard core, of 1 mil Orthonol, weighs 0.6 lbs. This transformer was fabricated and installed in a compact cylindrical case with internal condensing fins and an integral forced air heat exchanger. The case is filled with Freon 113. This case design, which conforms to the cylindrical shape of the transformer, was selected to provide data on compact packaging. The unitrode rectifier stack is located external to the case, inside a cooling shroud between the transformer case and an end mounted cooling fan. The compact package measures about 6 inches O.D., by 12 inches in length. (See Fig. 11). Fabrication and testing of this unit was completed, and the assembly was delivered to the Air Force, with a complete drawing package on June 9, 1977.

### 3.2.3 Transformer Impedance

Additional tests were performed on the water cooled and the air cooled transformers to determine more about their impedance characteristics. They were driven with variable width pulses at a PRF of 400 HZ. The pulse rise time was about  $0.1 \mu\text{Sec}$ . The pulse width was varied from 100 to 1 Sec. while the input and output waveforms were simultaneously displayed on an oscilloscope. The waveforms were substantially identical at  $100 \mu\text{Sec}$ . and exhibited noticeable distortion at  $10 \mu\text{Sec}$ . under matched impedance loading. All of these measurements were made at low excitation. From these preliminary tests, it appears that the transformer impedances are well below the maximum specified. These tests have shown the importance of leakage inductance and shunt capacitance. It is obvious for instance that the LC product should be made as small as possible for good wideband or pulse performance. Expressions for leakage inductance and shunt capacitance were derived for fully interleaved pia wound transformers. The leakage inductance is expressed in Equation (1).

$$L_{lp} = N_{pies} \left\{ \left[ \pi \mu_0 N_{dp}^2 (OD^2 - ID^2) / (OD - ID)^2 \right] \left[ t_1 + (t_p + t_2) \right] \right\} \quad (1)$$



SCALE 1/1  
10 KW INV. TRANS  
(105 C. SINGLE C-CORE)

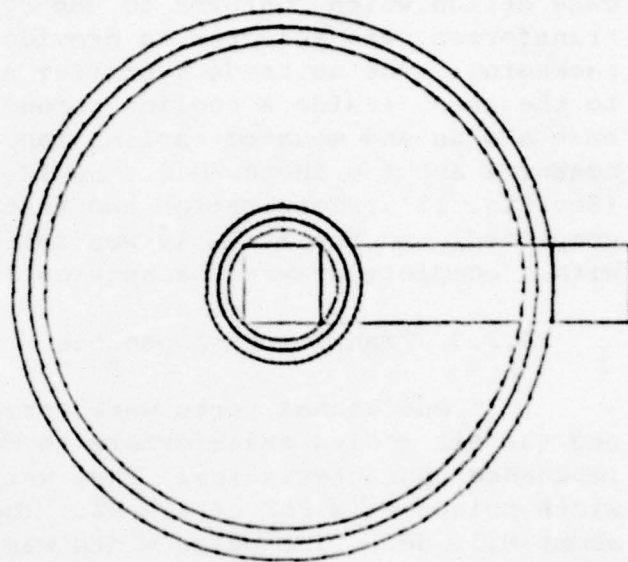


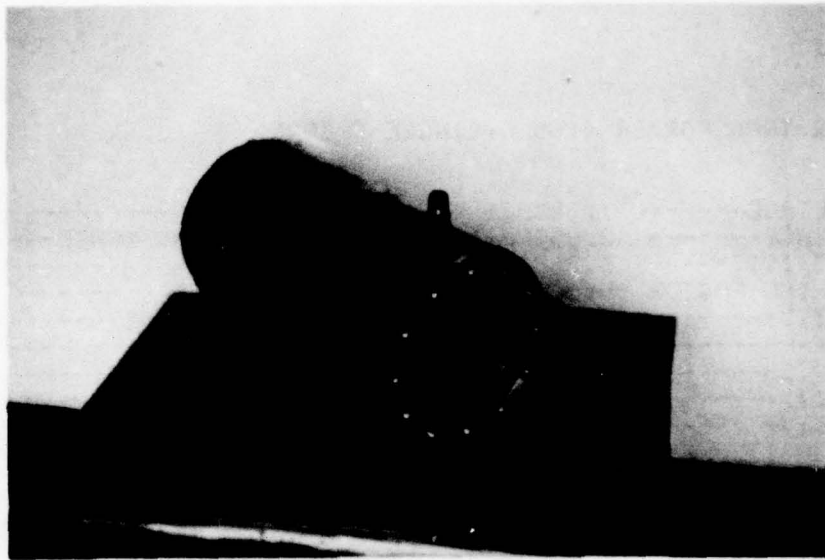
Figure 9 - Final Design - 10 KVA Transformer

DATA FILE # 21

10 KW INVERTER TRANSFORMER (105 C SINGLE C CORE)

1 OUTPUT VOLTAGE-----	1.0000E+04	51 REGULATION-----	1.8122E-02
2 INPUT VOLTAGE-----	2.8500E+02	52 MIN COOLING SPACE---	1.0000E-02
3 WIRE RESISTIVITY----	6.7800E-07	53 OUTPUT CURRENT-----	1.0000E+00
4 CORE STACKING FACTOR	8.5000E-01	54 INPUT POWER-----	1.0173E+04
5 FLUX DENSITY-----	5.0000E+04	55 INPUT CURRENT-----	3.5695E+01
6 FREQUENCY-----	1.0000E+04	56 PRIMARY LOSS-----	6.5776E+01
7 NO. SEC. PIES-----	4.0000E+00	57 SECONDARY LOSS-----	1.1873E+02
8 WIRE DENSITY-----	3.2400E-01	58 -----	0.0000E+00
9 CORE DENSITY-----	3.0200E-01	59 -----	0.0000E+00
10 COOLANT DENSITY-----	5.6500E-02	60 -----	0.0000E+00
11 PRI. HEATING RATE---	6.6367E-01	61 PRI. HEIGHT-----	3.2800E-01
12 SEC. HEATING RATE---	2.7246E-01	62 SEC. HEIGHT-----	2.7307E-01
13 CORE DISS. RATE-----	8.0000E+01	63 WINDING HEIGHT-----	1.4211E+00
14 CORE LEG WIDTH-----	5.0000E-01	64 PRI. MEAN LENGTH----	6.5049E+00
15 CORE LEG DEPTH-----	5.0000E-01	65 SEC. MEAN LENGTH----	6.4484E+00
16 PRI. TURNS PER PIE--	1.5006E+01	66 PRI. RES.-----	5.1625E-02
17 SPOOL THICKNESS-----	6.6500E-02	67 SEC. RES.-----	1.1873E+02
18 PRI. TURN SPACE-----	6.0000E-04	68 COPPER LOSS-----	1.8450E+02
19 PRI. PIE SPACE-----	6.0000E-04	69 WINDING VOL.-----	3.0945E+00
20 PRI. SPACE OUTSIDE--	2.5000E-02	70 WINDING WEIGHT-----	1.0026E+00
21 SEC. TURN SPACE-----	1.4000E-03	71 CORE VOL.-----	2.0000E+00
22 SEC. PIE SPACE-----	1.1000E-03	72 CORE WEIGHT-----	6.0400E-01
23 SEC. SPACE OUTSIDE--	0.0000E+00	73 CORE LOSS-----	4.8320E+01
24 EFF. INCR.-----	1.0000E-02	74 TOT. PWR. LOSS-----	2.3282E+02
25 BREAKDOWN FACTOR----	2.0000E-05	75 -----	0.0000E+00
26 CORE FORM FACTOR----	1.0000E+00	76 -----	0.0000E+00
27 -----	0.0000E+00	77 TANK VOL.-----	3.5000E+01
28 PWR. INCR.-----	5.0000E+02	78 COOLANT VOL.-----	2.9905E+01
29 SEC INNER KEEPBACK--	7.0057E-02	79 COOLANT WEIGHT-----	1.6897E+00
30 PRI. WIRE GAUGE-----	1.2000E+01	80 RES. SINGLE PRI. PIE	1.2906E-02
31 SEC. WIRE GAUGE-----	3.0000E+01	81 RES. SINGLE SEC. PIE	2.9681E+01
32 MAX PRI. HEAT TRANS.	1.0000E+00	82 VOLTS PER TURN-----	4.7175E+00
33 MAX SEC. HEAT TRANS.	5.0000E-01	83 SEC. PIE I.D.-----	1.0052E+00
34 -----	0.0000E+00	84 SEC-PIE O.D.-----	3.1000E+00
35 -----	0.0000E+00	85 SEC OUTER KEEPBACK--	2.0000E-01
36 MAX PWR. OUTPUT-----	1.0000E+04	86 INCR. EFF.-----	9.8299E-01
37 PRI. I.D.-----	8.4011E-01	87 PRI-SEC SPACER-----	5.0000E-03
38 PRI. O.D.-----	3.3010E+00	88 SEPARATION ADJUST---	2.0000E-01
39 THICKNESS SEC. PIE--	6.8267E-02	89 CORE IDENTIFICATION-	1.6100E+03
40 PRI. WIRE DIA.-----	8.0801E-02	90 SEC O.D. ADJUST-----	0.0000E+00
41 SEC. WIRE DIA.-----	1.0028E-02	91 TOT. HEATING RATE---	2.7772E+00
42 WINDOW WIDTH-----	1.5000E+00	92 ASSEMBLY SEPARATION-	2.5000E-01
43 WINDOW HEIGHT-----	1.5000E+00	93 MAX PRI GAUGE-----	2.0000E+01
44 PRI. TURNS-----	6.0023E+01	94 MAX SEC GAUGE-----	4.0000E+01
45 SEC. TURNS-----	2.1449E+03	95 SPECIFIC WEIGHT-----	3.2963E-01
46 PRI. PIES-----	4.0000E+00	96 TURNS RATIO-----	3.5735E+01
47 SEC. TURNS PER PIE--	5.3623E+02	97 -----	0.0000E+00
48 SEC I.D. ADJUST-----	2.5000E-02	98 -----	0.0000E+00
49 EFFICIENCY-----	9.7725E-01	99 -----	0.0000E+00
50 TOT. WEIGHT-----	3.2963E+00	100 PWR. OUTPUT-----	1.0000E+04

Figure 10. Final Design Data - 10 KVA Transformer



(a) Assembled



(b) Disassembled

Figure 11 - Air Cooled 10 KW T/R Unit

Where

- $N_{\text{pies}}$  = Number of Pies (K7)
- $\mu_o$  =  $3.19 \times 10^{-8}$  Henries/inch
- $N_{\text{dp}}$  = Number of turns per primary pie (K 16)
- O.D. = Pie outside diameter (primary) (K 38)
- I.D. = Pie inside diameter (primary) (K 37)
- $t_i$  = Primary to Secondary insulation thickness (K 87)
- $t_p$  = Primary Pie thickness (K 40)
- $t_s$  = Secondary Pie thickness (K 39)

Leakage inductance is assigned to array number K 75.

The interwinding capacitance is

$$C = N_{\text{pies}} \epsilon \epsilon_o \pi (OD^2 - ID^2) / 4 l_i \quad (2)$$

Where

- $\epsilon$  = dielectric constant of primary to secondary insulation (K22)
- $\epsilon_o$  = permittivity of free space

The self-resonant frequency is

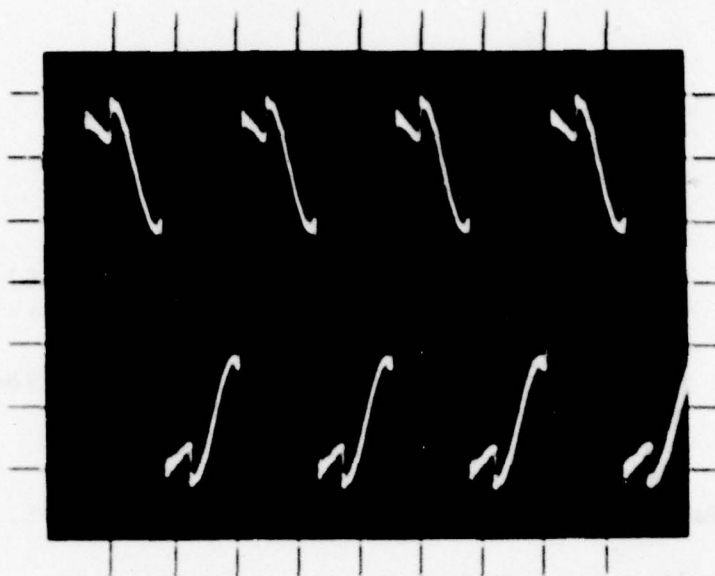
$$f = 1 / (2\pi \sqrt{L_{lf} C}) \quad (3)$$

These equations were evaluated for the parameters of the water cooled and the air cooled transformers. The results were close to the measured values, being low in each case by about 20%. This contrasts with the same type of calculations for layer wound transformers, which tend to be high by as much as 50%.

#### 3.2.4 10 KW Inverter Tests

The 10 KW inverter supplied by Power Electronics Associates, Inc. was integrated with both the air cooled and the water cooled transformer rectifier units. After the inverter was tested with a resistive load to verify its performance the air cooled T/R unit was connected to the inverter. The input voltage was increased in 100 volt increments to a maximum of 600 volts. The input voltage and current waveforms are shown in Fig. 12, for the inverter

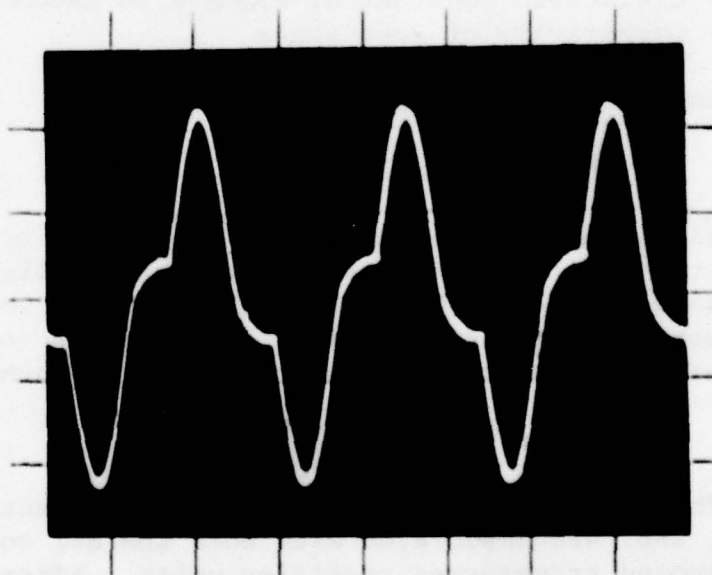
Transformer  
Input  
Voltage  
100 V/div



Time - 50 Micro Seconds/Division

(a)

Transformer  
Input  
Current  
40 A/div



Time - 50 Micro Seconds/ Division

(b)

Figure 12. Inverter Waveforms

operating at maximum power. The D.C. output voltage and current were 9.2 KV and 0.92 AMPS. respectively. The output power of 8,464 watts was 15% below rated power. At first, it was believed that this was due to an error in the transformer turns ratio computation, but examination of the voltage waveform in Fig. 12 shows that the peak and not the RMS voltage was 300 volts. The RMS input voltage was re-estimated to be about 250 volts. The maximum operating frequency was measured to be 7,850 Hz, not 10 KHz.

During the testing of this transformer with the inverter a slight overheating of the case input terminals was detected. These terminals were 8-32 brass machine screws. Since there was ample room in the case, they were replaced with 5/16 inch copper studs, which cured the problem. As previously stated in Para. 3.2.1, the water cooled transformer unit delivered 9200 volts at 1.1 AMPS, to the load when integrated with the 10 KW inverter. The overall system efficiency was 89% at 10.12 KW.

The inverter was operated for approximately ten hours during the testing of both T/R units, with the longest single run lasting 30 minutes.

### 3.3 200 KW Inverter Transformers

#### 3.3.1 General

The original plan was for the 200 KW transformer rectifier system to be a scaled-up version of the 10 KW systems. As the work on the 10 KW transformer progressed, it was evident that direct scaling was not possible. Therefore, based on studies of the 10 KW systems, significant improvements to the computer programs were implemented, and a series of new computer programs were developed on the HP 9830. These programs were utilized for the design and development of the 200 KW transformer. See Appendix B for detailed descriptions.

There were new fabrication problems which were solved during the design of the 200 KW transformer. From the preliminary design programs, a 155°C unit design was selected to base the fabrication procedures on. Tests were run on glues,

epoxies, and insulation materials suitable for this temperature and acceptable materials were selected. Experiments in winding large pies were conducted. Eight inch mandrels were used to wind coils for evaluation. Problems were encountered with winding wire sizes below #30 AWG because of the large tangential velocity range. It was found that the motor speed should be controlled for constant wire speed through the feed and tensioning system, to avoid breaking the wire. Some consideration had to be given to methods of coating the wire during the coil winding operation, because of the difficulty of obtaining double coated wire in all sizes. Also, special care had to be taken to avoid dimensional variations in the large pie windings, because of the growth of winding eccentricities with radius. All of the winding problems were eventually solved and sample large diameter coils were made which fully verified the fabrication procedures.

An investigation of the selection and packaging of the rectifiers was also conducted. It was found that single rectifiers can be up-rated by a factor of five to ten in current carrying capacity, if properly cooled. An analysis was made of the uprating possible with certain rectifier structures immersed in Freon 113. It was found that the upper limit of operation of the All4 series of General Electric rectifiers could be raised from the specified maximum of 1.1 Amperes to 8 Amperes. Fast recovery is needed only in those cases where additional losses of 10% cannot be tolerated. It was finally decided to incorporate the rectifiers in bridge configuration as part of the individual pies. The rectifiers are mounted on the corners and along one side of the primary/secondary separation plates. The rectifiers selected for the final design are general instrument type RGP 30M, fast recovery (500 ns.), 1000 PIV diodes.

It was specified by Dr. Schwartz of Power Electronics Associates, Inc., that capacitors should be installed across the DC output of the bridge rectifiers. Centralab 0.0015 ufd, 1000 VDCW capacitors were selected. These are also mounted on the primary/secondary separation plates. Figure 13 shows the integration of the rectifiers and capacitors on the pies.

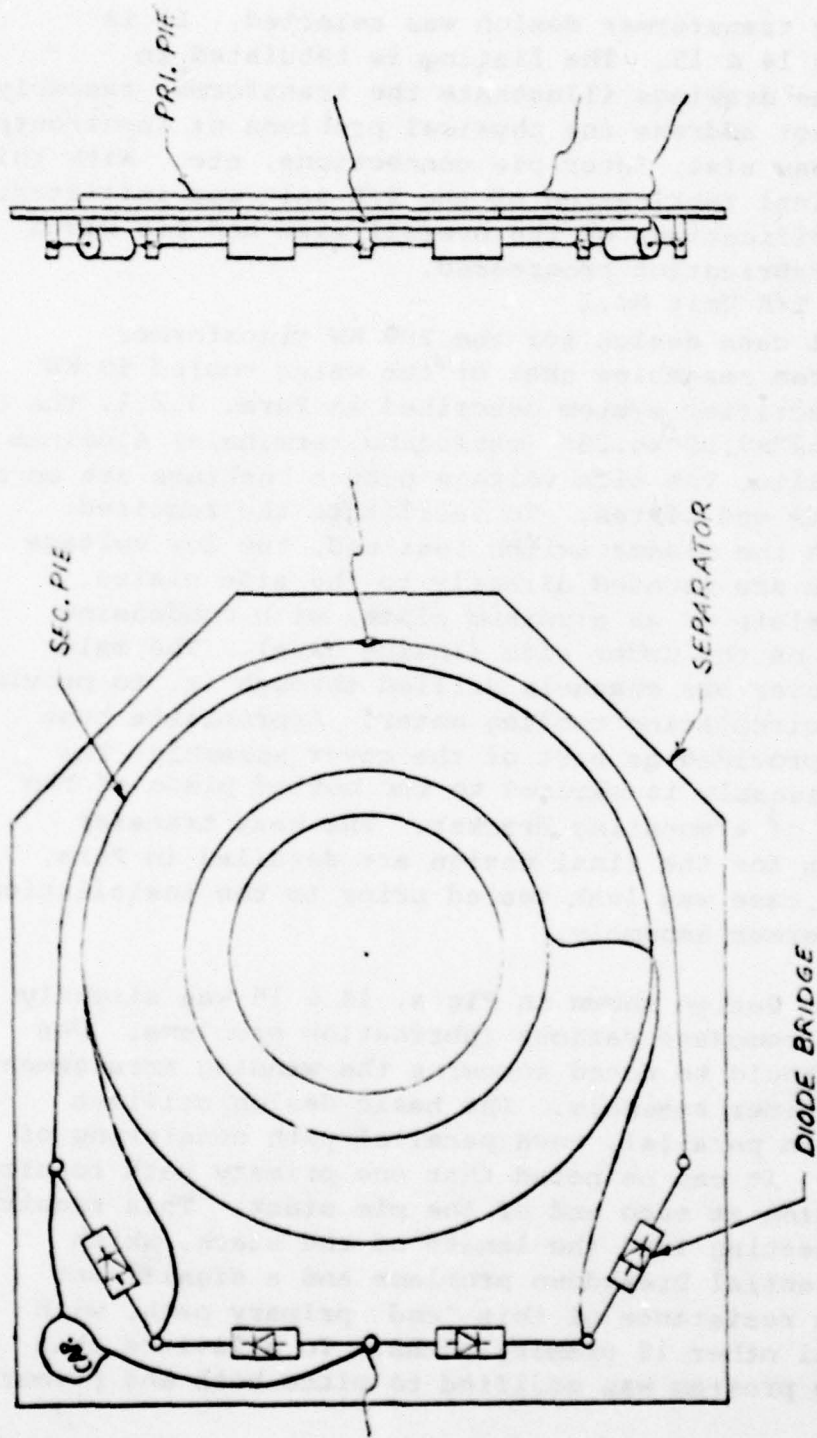


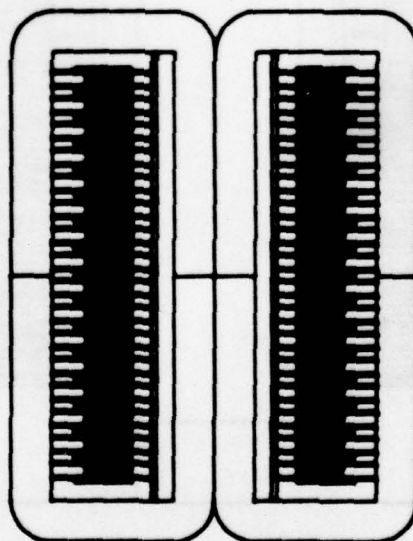
Figure 13. Pre-Mounted Diode Bridge Configuration

The basic transformer design was selected. It is shown in Fig's 14 & 15. The listing is tabulated in Fig. 16. These drawings illustrate the transformer assembly only, and do not address the physical problems of input/output connectors, case size, inter-pie connections, etc. With this design, the final fabrication of the T/R unit was initiated. Some minor modifications of the overall size and pie width resulted as fabrication progressed.

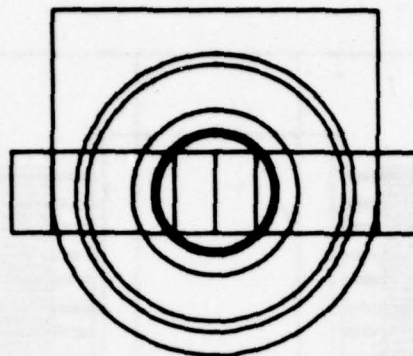
### 3.3.2 200 KW T/R Unit No.1

The final case design for the 200 KW transformer rectifier system resembles that of the water cooled 10 KW transformer rectifier system described in Para. 3.2.1. The case consists of a 8.62"x7.00"x6.25" (excluding terminals) aluminum box with 0.25" thick walls. The high voltage output bushings are mounted directly to the end plates. To facilitate the required interface with the plasma switch test bed, the low voltage input bushings are mounted directly to the side plates. The cover consists of an aluminum plate, with condensing fins machined on the under side (inside case). The main body of the cover has channels drilled through it, to provide passages for circulating cooling water. Appropriate hose fittings are provided as part of the cover assembly. The transformer assembly is secured to the bottom plate of the case by means of a mounting bracket. The heat transfer considerations for the final design are detailed in Para. 3.3.3. The completed case was leak tested prior to the installation of the transformer assembly.

The basic design shown in Fig's. 14 & 15 was slightly modified to accomodate various fabrication problems. One change that should be noted concerns the winding arrangements in the transformer assembly. The basic design utilizes 16 primaries in parallel, each parallel path consisting of two sections. It can be noted that one primary path resulted with one section at each end of the pie stack. This required an axial connecting lead the length of the stack, which presented potential breakdown problems and a significant difference in resistance of this "end" primary path, with respect to all other 15 primary paths. To alleviate this condition the program was modified to place both end primary



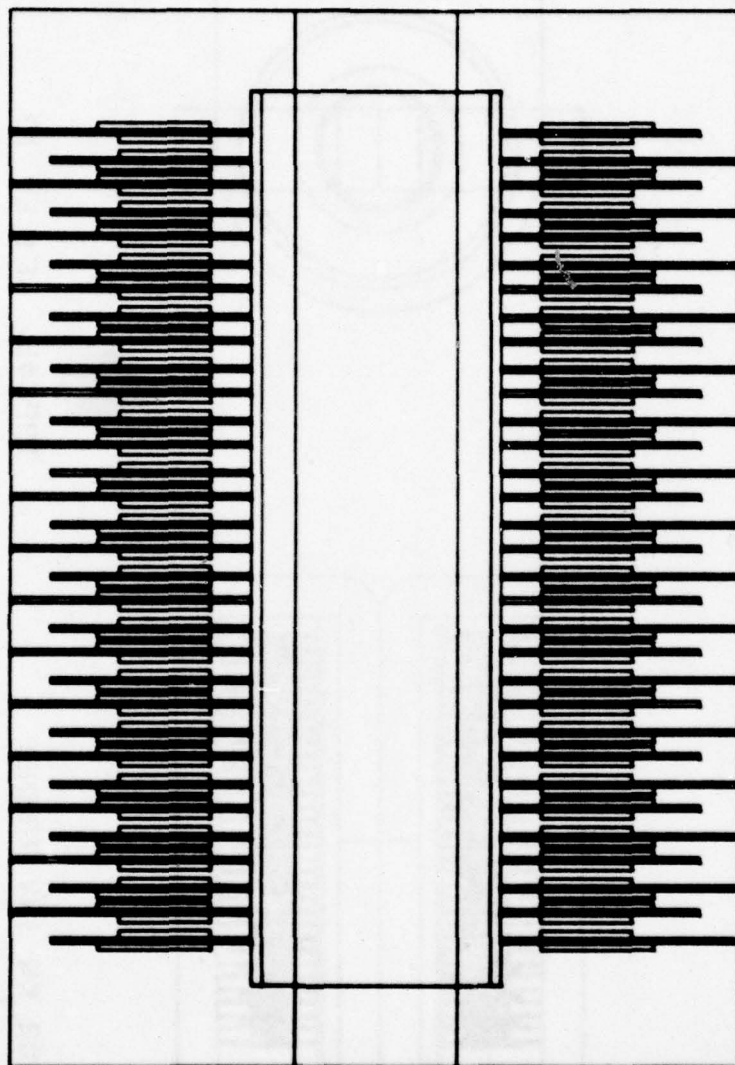
200 KW INV TRANSF



TAPE#9, FILE# 13

SCALE 1 / 2 ; 7 X 10

Figure 14. 200 KVA Transformer



200 KW INV TRANSF

TAPE#9, FILE# 13

TOP VIEW

SCALE 1/1 ; 7 X 10

Figure 15. Detailed View - 200 KVA Transformer

1 DC OUTPUT VOLTAGE---	2.5000E+04	51 REGULATION-----	5.2732E-03
2 INPUT VOLTAGE-----	5.7000E+02	52 MIN COOLING SPACE---	3.1250E-02
3 WIRE RESISTIVITY---	7.4300E-07	53 DC OUTPUT CURRENT---	8.0000E+00
4 CORE STACKING FACTOR	8.5000E-01	54 INPUT POWER-----	2.0242E+05
5 FLUX DENSITY-----	5.0000E+04	55 INPUT CURRENT-----	4.9008E+02
6 FREQUENCY-----	1.0000E+04	56 PRIMARY LOSS-----	6.6939E+02
7 NO. PIES-----	3.2000E+01	57 SECONDARY LOSS-----	8.0960E+02
8 WIRE DENSITY-----	3.2400E-01	58 HEIGHT-----	5.0000E+00
9 CORE DENSITY-----	3.0200E-01	59 WIDTH-----	4.5000E+00
10 RADIAL ADJUST-----	0.0000E+00	60 LENGTH-----	6.5000E+00
11 VOLTAGE FORM FACTOR-	1.0000E+00	61 PRI. O.D.-----	3.4305E+00
12 CURRENT FORM FACTOR-	1.3800E+00	62 SEC. O.D.-----	3.1647E+00
13 CORE DISS. RATE-----	8.0000E+01	63 WINDING HEIGHT-----	5.3456E+00
14 CORE LEG WIDTH-----	5.0000E-01	64 PRI. MEAN LENGTH----	2.1854E+00
15 CORE LEG DEPTH-----	1.0000E+00	65 SEC. MEAN LENGTH----	1.7679E+00
16 PRI. TURNS PER PIE--	1.6725E+01	66 PRI. RES.-----	2.7871E-03
17 SPOOL THICKNESS----	6.2500E-02	67 SEC. RES.-----	6.6425E+00
18 PRI. INSUL SPACE----	6.0000E-04	68 COPPER LOSS-----	1.4790E+03
19 WINDOW LENGTH ADJ---	2.5000E-01	69 WINDING VOL.-----	2.3305E+00
20 PRI. SPACE OUTSIDE--	2.1783E-01	70 WINDING WEIGHT-----	7.5509E-01
21 SEC. INSUL SPACE----	1.4000E-03	71 CORE VOL.-----	1.5768E+01
22 RECTIFIER FACTOR----	1.0100E+00	72 CORE WEIGHT-----	4.7620E+00
23 RECTIFIER PRV-----	1.0000E+03	73 CORE LOSS-----	3.8096E+02
24 RECT. FWD. VOLT DROP	1.1000E+00	74 TOT. PWR. LOSS-----	2.4231E+03
25 BREAKDOWN FACTOR----	1.0000E-05	75 RECTIFIER LOSSES----	5.6320E+02
26 CORE FORM FACTOR----	2.0000E+00	76 LEAKAGE INDUCTANCE--	8.0191E-07
27 -----	0.0000E+00	77 TANK VOL.-----	1.4364E+02
28 RECT SAFETY FACTOR--	1.2000E+00	78 COOLANT VOL.-----	1.1118E+02
29 SEC INNER KEEPBACK--	2.5000E-01	79 COOLANT WEIGHT-----	6.2817E+00
30 PRI. WIRE GAUGE-----	1.8000E+01	80 RES. SINGLE PRI. PIE	2.2297E-02
31 SEC. WIRE GAUGE-----	2.4000E+01	81 RES. SINGLE SEC. PIE	2.0758E-01
32 PRI. HEAT TRANS.----	3.5000E+00	82 VOLTS PER TURN-----	1.7000E+01
33 SEC. HEAT TRANS.----	5.5000E+00	83 PIE I.D.-----	2.0392E+00
34 NO. PARALLEL SECS.--	1.0000E+00	84 PIE O.D.-----	3.5000E+00
35 NO. PARALLEL PRIS.--	1.6000E+01	85 SEC OUTER KEEPBACK--	2.5000E-01
36 MAX PWR. OUTPUT-----	2.0000E+05	86 TOTAL NO. RECTIFIERS	1.2800E+02
37 RECTIFIER WGT. %02--	4.0000E-02	87 PRI-SEC SPACER-----	3.1250E-02
38 RECTIFIER THICKNESS-	2.1000E-01	88 SEPARATION ADJUST---	-1.2710E-02
39 THICKNESS SEC. PIE--	4.5809E-02	89 CAPACITANCE-----	4.7770E-09
40 PRI. WIRE DIA.-----	4.0305E-02	90 # LAYERS, PRIMARY----	1.0000E+00
41 SEC. WIRE DIA.-----	2.0105E-02	91 THICKNESS PRI. PIE--	4.1505E-02
42 WINDOW WIDTH-----	1.5000E+00	92 SECONDARY SEPARATION	5.1355E-02
43 WINDOW HEIGHT-----	5.5300E+00	93 PRIMARY SEPARATION--	3.1250E-02
44 PRI. TURNS PER/PATH--	3.3449E+01	94 NO. RECTS. PER LEG--	2.0000E+00
45 SEC. TURNS-----	1.4937E+03	95 SPECIFIC WEIGHT-----	6.0594E-02
46 SPOOL O.D.-----	1.5392E+00	96 TURNS RATIO-----	4.4657E+01
47 SEC. TURNS PER PIE--	4.6679E+01	97 BRIDGE INPUT VOLTAGE	1.5825E+03
48 # LAYERS, SEC.-----	2.0000E+00	98 AC OUTPUT VOLTAGE---	2.5320E+04
49 EFFICIENCY-----	9.8803E-01	99 AC OUTPUT CURRENT---	1.1040E+01
50 TOT. WEIGHT-----	1.2119E+01	100 WIDTH ADJUST-----	5.0000E-01

Figure 16. Detailed Listing - 200 KVA Transformer

pies at the same end of the stack. The final end design configuration is shown in Fig's. 17 & 18. The core material is 1 mil Orthonol, #20 AWG wire is used for the primary pies, and #24 AWG is used for the secondary pies. Both primary and secondary have 32 pies each. AC input is 570 volts at 504.6 amps. D.C. output is 25 KV at 8.0 amps. The final output listing is shown in Fig. 19.

All of the secondary pies fabricated for the first transformer assembly were calibrated with a turns-ratio bridge at 10 KHz. Also, the assemblies were short circuit tested prior to installation on the transformer assembly. Tap changing on the transformer assembly may be accomplished by moving the positive output connection to the desired pie assembly. Upon completion of the transformer assembly, the unit was successfully tested for open circuits and leakage inductance. Measured leakage inductance of 0.6 uhy was identical to the calculated value. The final T/R Unit was successfully tested for dielectric insulation as follows.

- a) Primary-secondary (35KV.RMS, with output shorted)
- b) Primary-case (1.5KV.RMS)
- c) Secondary-case (35KV.RMS, with output shorted)
- d) PRV (35 KV.DC.)

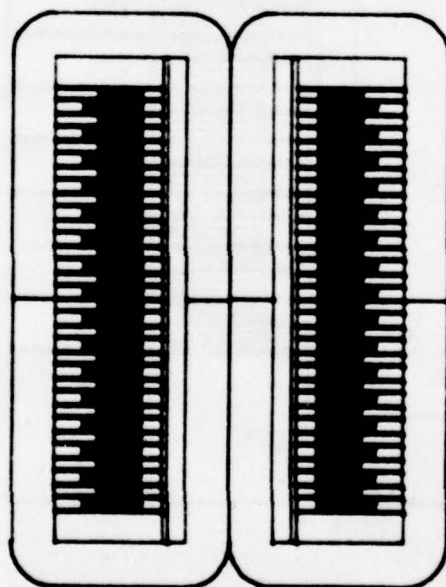
The 200 KW T/R Unit No. 1 was delivered in early February 1978, to the State University of New York at Buffalo (SUNYAB), for installation in the plasma switch test bed, per U.S. Air Force direction.

To date, only pulse testing to 340 KW peak for 6 (six) 10 KHz cycles at a time has been performed.

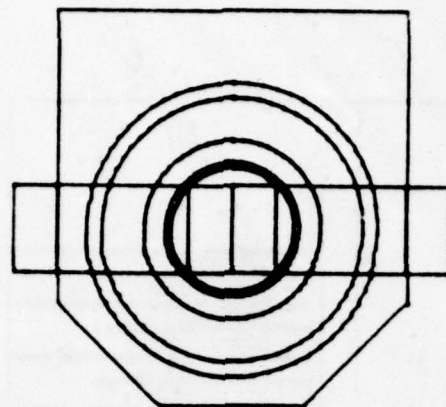
### 3.3.3 200 KW T/R System No. 2

#### 3.3.3.1 Modified Design

This transformer differs from that of the first unit in that it has two independent primaries for operation from two inverter outputs of 100 KW each. After considerable analysis and discussion it was agreed with Dr. Schwartz that the average voltage across each primary winding would be 520 volts. Figure 20 presents the detailed design output listing. The core material is 1 mil Orthonol, #24 AWG wire is used for both the primary and secondary pies, and there are 32 primary and secondary pies. AC input is 1,040 volts at 277.4 amps. DC output is 25 KV at 8.0 amps. Figures 21 and 22 show the physical arrangement of T/R Unit No. 2.



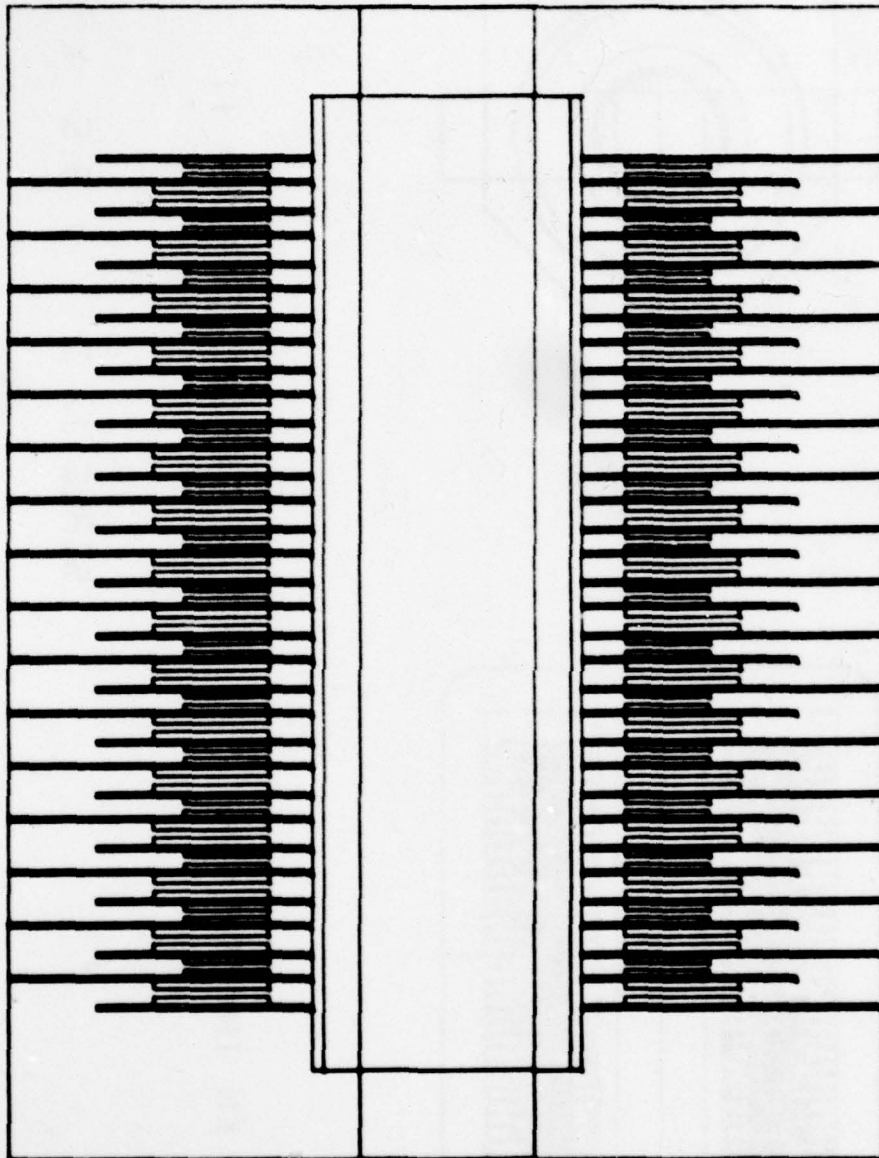
200 KW INV TRANSF



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SCALE 1/2 ; 0.5 X 11

Figure 17 - Final Design - 200 KVA Transformer



200 KW INV TRANSF

TAPE#5, FILE# 11

TOP VIEW

SCALE 1/1 ; 8.5 X 11

Figure 18 - Final Design - 200 KVA Transformer

FILE # 11

1 DC OUTPUT VOLTAGE----	2.5000E+04	51 REGULATION-----	2.0112E-01
2 INPUT VOLTAGE-----	5.7000E+02	52 MIN COOLING SPACE----	3.0000E-02
3 WIRE RESISTIVITY----	7.4300E-07	53 DC OUTPUT CURRENT----	8.0000E+00
4 CORE STACKING FACTOR	8.5000E-01	54 INPUT POWER-----	2.0842E+05
5 FLUX DENSITY-----	5.0000E+04	55 INPUT CURRENT-----	5.0460E+02
6 FREQUENCY-----	1.0000E+04	56 PRIMARY LOSS-----	3.4064E+03
7 NO. PIES-----	3.2000E+01	57 SECONDARY LOSS-----	4.0704E+03
8 WIRE DENSITY-----	3.2400E-01	58 HEIGHT-----	5.0000E+00
9 CORE DENSITY-----	3.0200E-01	59 WIDTH-----	5.0000E+00
10 RADIAL ADJUST-----	0.0000E+00	60 LENGTH-----	6.5000E+00
11 VOLTAGE FORM FACTOR--	1.0000E+00	61 PRI. O.D.-----	2.9998E+00
12 CURRENT FORM FACTOR--	1.3800E+00	62 SEC. O.D.-----	3.3466E+00
13 CORE DISS. RATE-----	8.0000E+01	63 WINDING HEIGHT-----	5.3636E+00
14 CORE LEG WIDTH-----	5.0000E-01	64 PRI. MEAN LENGTH-----	7.9153E+00
15 CORE LEG DEPTH-----	1.0000E+00	65 SEC. MEAN LENGTH-----	8.4600E+00
16 PRI. TURNS PER PIE--	1.3588E+01	66 PRI. RES.-----	2.1405E-01
17 SPOOL THICKNESS-----	6.2500E-02	67 SEC. RES.-----	3.3396E+01
18 PRI. INSUL SPACE----	1.3000E-03	68 COPPER LOSS-----	7.4767E+03
19 WINDOW LENGTH ADJ----	5.0000E-01	69 WINDING VOL.-----	6.8201E+00
20 PRI. SPACE OUTSIDE--	3.3869E-01	70 WINDING WEIGHT-----	2.2097E+00
21 SEC. INSUL SPACE----	1.7000E-03	71 CORE VOL.-----	1.5795E+01
22 RECTIFIER FACTOR-----	1.0100E+00	72 CORE WEIGHT-----	4.7702E+00
23 RECTIFIER PRV-----	1.0000E+03	73 CORE LOSS-----	3.8161E+02
24 RECT. FWD. VOLT DROP	1.1000E+00	74 TOT. PWR. LOSS-----	8.4215E+03
25 BREAKDOWN FACTOR-----	1.0000E-05	75 RECTIFIER LOSSES-----	5.6320E+02
26 CORE FORM FACTOR-----	2.0000E+00	76 LEAKAGE INDUCTANCE--	6.3322E-07
27 -----	2.5000E-02	77 TANK VOL.-----	1.5994E+02
28 RECT SAFETY FACTOR--	1.2000E+00	78 COOLANT VOL.-----	1.2133E+02
29 SEC INNER KEEPBACK--	2.5000E-01	79 COOLANT WEIGHT-----	6.8552E+00
30 PRI. WIRE GAUGE-----	2.0000E+01	80 RES. SINGLE PRI. PIE	1.0703E-01
31 SEC. WIRE GAUGE-----	2.4000E+01	81 RES. SINGLE SEC. PIE	1.0436E+00
32 PRI. HEAT TRANS.-----	2.8000E+01	82 VOLTS PER TURN-----	1.7000E+01
33 SEC. HEAT TRANS.-----	2.3000E+01	83 PIE I.D.-----	2.0392E+00
34 NO. PARALLEL SECS.--	1.0000E+00	84 PIE O.D.-----	3.5000E+00
35 NO. PARALLEL PRIS.--	1.6000E+01	85 SEC OUTER KEEPBACK--	2.5000E-01
36 MAX PWR. OUTPUT-----	2.0000E+05	86 TOTAL NO. RECTIFIERS	1.2800E+02
37 RECTIFIER WGT. +02--	4.0000E-02	87 PRI-SEC SPACER-----	2.5000E-02
38 RECTIFIER THICKNESS--	2.1000E-01	88 SEPARATION ADJUST---	6.4851E-02
39 THICKNESS SEC. PIE--	4.7009E-02	89 CAPACITANCE-----	4.9350E-09
40 PRI. WIRE DIA.-----	3.1964E-02	90 # LAYERS, PRIMARY----	1.0000E+00
41 SEC. WIRE DIA.-----	2.0105E-02	91 THICKNESS PRI. PIE--	3.4564E-02
42 WINDOW WIDTH-----	1.5000E+00	92 SECONDARY SEPARATION	4.5767E-02
43 WINDOW HEIGHT-----	5.5000E+00	93 PRIMARY SEPARATION--	4.0937E-02
44 PRI. TURNS PER PATH--	2.7176E+01	94 NO. RECTS. PER LEG--	2.0000E+00
45 SEC. TURNS-----	1.5111E+03	95 SPECIFIC WEIGHT-----	7.0776E-02
46 SPOOL O.D.-----	1.5392E+00	96 TURNS RATIO-----	5.5605E+01
47 SEC. TURNS PER PIE--	4.7223E+01	97 BRIDGE INPUT VOLTAGE	1.5825E+03
48 # LAYERS, SEC.-----	2.0000E+00	98 AC OUTPUT VOLTAGE----	2.5320E+04
49 EFFICIENCY-----	9.5959E-01	99 AC OUTPUT CURRENT----	1.1040E+01
50 TOT. WEIGHT-----	1.4155E+01	100 WIDTH ADJUST-----	1.0000E+00

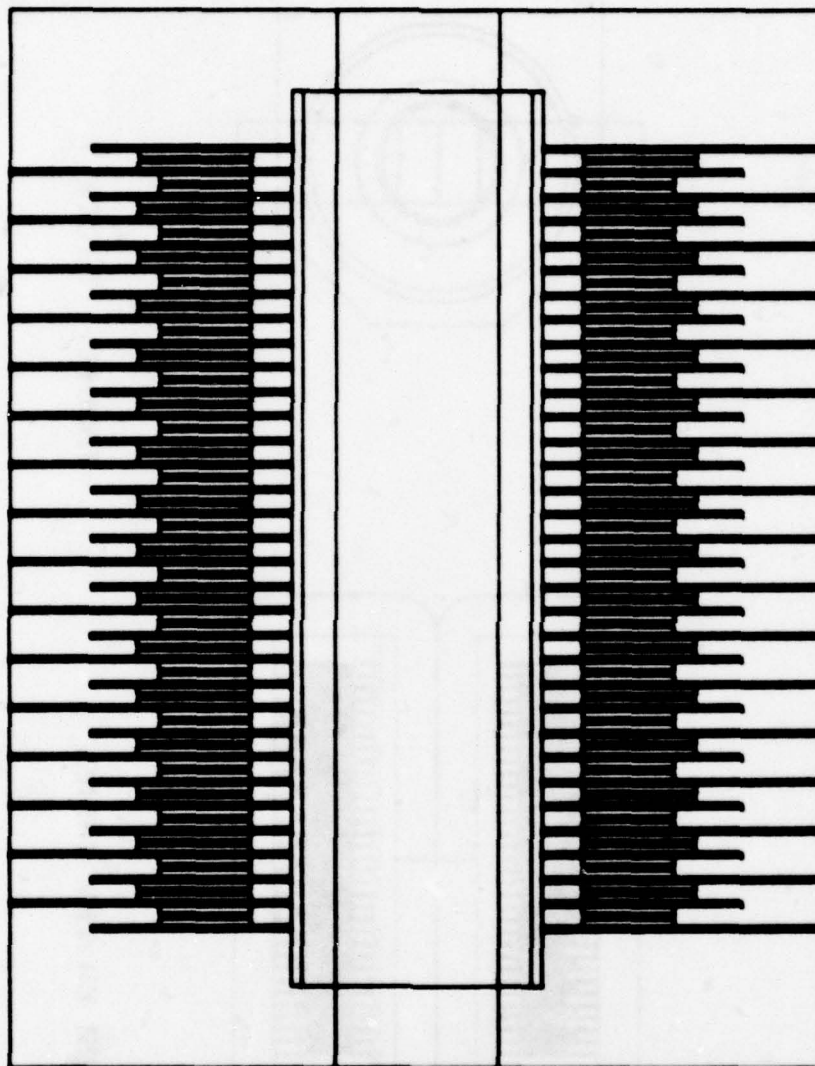
Figure 19. Detailed Listing - Final Design, 200 KVA Transformer

FILE # 7

200 KW INV TRANSF

1 DC OUTPUT VOLTAGE---	2.5000E+04	51 REGULATION-----	5.2732E-03
2 INPUT VOLTAGE-----	5.7000E+02	52 MIN COOLING SPACE---	3.1250E-02
3 WIRE RESISTIVITY---	7.4300E-07	53 DC OUTPUT CURRENT---	8.0000E+00
4 CORE STACKING FACTOR	8.5000E-01	54 INPUT POWER-----	2.0242E+05
5 FLUX DENSITY-----	5.0000E+04	55 INPUT CURRENT-----	4.9008E+02
6 FREQUENCY-----	1.0000E+04	56 PRIMARY LOSS-----	6.6939E+02
7 NO. PIES-----	3.2000E+01	57 SECONDARY LOSS-----	8.0960E+02
8 WIRE DENSITY-----	3.2400E-01	58 HEIGHT-----	5.0000E+00
9 CORE DENSITY-----	3.0200E-01	59 WIDTH-----	5.0000E+00
10 RADIAL ADJUST-----	0.0000E+00	60 LENGTH-----	6.5000E+00
11 VOLTAGE FORM FACTOR-	1.0000E+00	61 PRI. O.D.-----	3.4305E+00
12 CURRENT FORM FACTOR-	1.3900E+00	62 SEC. O.D.-----	3.1647E+00
13 CORE DISS. RATE----	8.0000E+01	63 WINDING HEIGHT-----	5.3565E+00
14 CORE LEG WIDTH-----	5.0000E-01	64 PRI. MEAN LENGTH----	2.1854E+00
15 CORE LEG DEPTH-----	1.0000E+00	65 SEC. MEAN LENGTH----	1.7679E+00
16 PRI. TURNS PER PIE--	1.6725E+01	66 PRI. RES.-----	2.7871E-03
17 SPOOL THICKNESS----	6.2500E-02	67 SEC. RES.-----	6.6425E+00
18 PRI. INSUL SPACE----	6.0000E-04	68 COPPER LOSS-----	1.4790E+03
19 WINDOW LENGTH ADJ----	5.0000E-01	69 WINDING VOL.-----	2.3305E+00
20 PRI. SPACE OUTSIDE--	3.3736E-01	70 WINDING WEIGHT-----	7.5509E-01
21 SEC. INSUL SPACE----	1.4000E-03	71 CORE VOL.-----	1.5785E+01
22 RECTIFIER FACTOR----	1.0100E+00	72 CORE WEIGHT-----	4.7670E+00
23 RECTIFIER PRV-----	1.0000E+03	73 CORE LOSS-----	3.8136E+02
24 RECT. FWD. VOLT DROP	1.1000E+00	74 TOT. PWR. LOSS-----	2.4235E+03
25 BREAKDOWN FACTOR----	1.0000E-05	75 RECTIFIER LOSSES----	5.6320E+02
26 CORE FORM FACTOR----	2.0000E+00	76 LEAKAGE INDUCTANCE--	8.0191E-07
27 -----	0.0000E+00	77 TANK VOL.-----	1.5981E+02
28 RECT SAFETY FACTOR--	1.2000E+00	78 COOLANT VOL.-----	1.2571E+02
29 SEC INNER KEEPBACK--	2.5000E-01	79 COOLANT WEIGHT-----	7.1027E+00
30 PRI. WIRE GAUGE-----	1.8000E+01	80 RES. SINGLE PRI. PIE	2.2297E-02
31 SEC. WIRE GAUGE-----	2.4000E+01	81 RES. SINGLE SEC. PIE	2.0758E-01
32 PRI. HEAT TRANS.----	3.5000E+00	82 VOLTS PER TURN-----	1.7000E+01
33 SEC. HEAT TRANS.----	5.5000E+00	83 PIE I.D.-----	2.0392E+00
34 NO. PARALLEL SECS.--	1.0000E+00	84 PIE O.D.-----	3.5000E+00
35 NO. PARALLEL PRIS.--	1.6000E+01	85 SEC OUTER KEEPBACK--	2.5000E-01
36 MAX PWR. OUTPUT-----	2.0000E+05	86 TOTAL NO. RECTIFIERS	1.2800E+02
37 RECTIFIER WGT. +02--	4.0000E-02	87 PRI-SEC SPACER-----	3.1250E-02
38 RECTIFIER THICKNESS-	2.1000E-01	88 SEPARATION ADJUST---	1.2710E-02
39 THICKNESS SEC. PIE--	4.5809E-02	89 CAPACITANCE-----	4.7770E-09
40 PPI. WIRE DIA.-----	4.0305E-02	90 # LAYERS, PRIMARY----	1.0000E+00
41 SEC. WIRE DIA.-----	2.0105E-02	91 THICKNESS PRI. PIE--	4.1505E-02
42 WINDOW WIDTH-----	1.5000E+00	92 SECONDARY SEPARATION	3.1250E-02
43 WINDOW HEIGHT-----	5.5000E+00	93 PRIMARY SEPARATION--	3.1250E-02
44 PRI. TURNS PER PATH--	3.3449E+01	94 NO. RECTS. PER LEG--	2.0000E+00
45 SEC. TURNS-----	1.4937E+03	95 SPECIFIC WEIGHT-----	6.4724E-02
46 SPOOL O.D.-----	1.5392E+00	96 TURNS RATIO-----	4.4657E+01
47 SEC. TURNS PER PIE--	4.6679E+01	97 BRIDGE INPUT VOLTAGE	1.5825E+03
48 # LAYERS, SEC.-----	2.0000E+00	98 AC OUTPUT VOLTAGE---	2.5320E+04
49 EFFICIENCY-----	9.8803E-01	99 AC OUTPUT CURRENT---	1.1040E+01
50 TOT. HEIGHT-----	1.2945E+01	100 WIDTH ADJUST-----	1.0000E+00

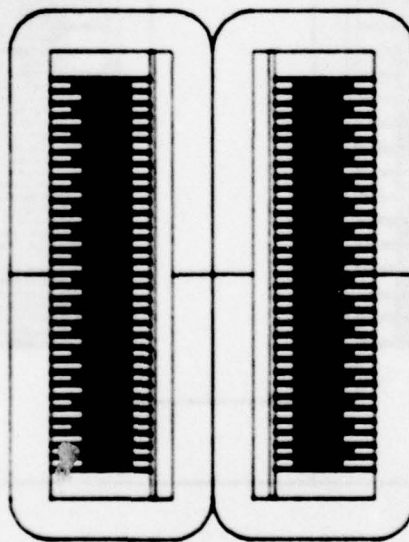
Figure 20. CAD Output Listing - 200 KVA Transformer No. 2.



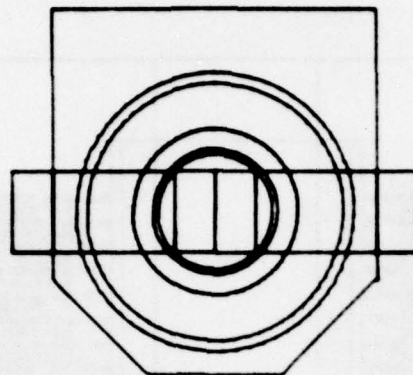
200 KW INV TRANSF  
TOP VIEW

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SCALE 1/1 ; 7 X 10

Figure 21. Winding Configuration - 200 KVA Transformer No. 2.



200 KW INV TRANSF



TAPESS, FILE# 7

SCALE 1/2 ; 7 X 10

Figure 22. 200 KVA T/R No. 2.

### 3.3.3.2 Final Design

Prior to fabrication, several additional temporary modifications to the design program were incorporated (See Figure 23).

The first modification was a change in the primary wire gauge, K(30), from #18 to #20. This change was made because of on-hand availability of the latter wire size in "P"-bond wire. The change had no significant effect on the transformer design.

The second modification consisted of deletion of lines 1450-1460 and 1670-1680, and replacement with:

1450 K(39) = .050

1670 K(91) = .039

These lines formerly computed the thicknesses of the secondary and primary pies, respectively. The computations were replaced by statements reflecting the pie thicknesses as measured on actual wound pies.

The third modification was a change in the thickness of the circuit board used as a primary-secondary spacer, K(87). This was originally a 0.031 in. thick board, but the purchased material was measured at 0.025 in. thick.

Design details dictated a differently sized cooling space between the secondary pies as opposed to the primary pies. Consequently, K(52) was set at 0.030 inches for the secondary cooling space, and K(27) was set at .025 inches and used for the primary cooling space. Appropriate changes were made in lines 1780 and 1790.

Since the core window height K(42), was fixed once the cores were ordered, K(43) was used as a fixed input parameter and computations of K(43) lines 1830 and 1840 were deleted, and the iteration process implied in line 1850 was bypassed by changing "1190" to 1880". Similarly, computation of the outside end space, K(20), which formerly varied with K(43) variations, were deleted (line 1800, and modifications to lines 1810 and 1980).

A listing of the transformer design parameters using the revised program is shown in Fig. 24. It will be noted that the net effect of these changes is negligible in terms of weight, efficiency, regulation, etc. They simply reflect the effects of the use of actual physical dimensions instead of analytically derived dimensions.

```

1000 CON L#(160),K#(210)
1010 DIM A#(40)
1020 DISP "FILE#":
1030 INPUT F
1040 K[120]=F
1050 LOAD DATA F
1060 K[115]=0
1070 DISP "K VALUE":
1080 STOP
1090 K[15]=K[26]*K[14]
1100 K[82]=4E-08*K[6]*K[14]*K[26]*K[15]*K[4]*K[5]*K[11]
1110 K[7]=INT(2*K[28]*K[1]/K[23]/K[94]+1)
1120 K[7]=K[7]+(K[7]/2#INT(K[7]/2))
1130 K[86]=2*K[94]*K[7]
1140 K[98]=K[7]*(K[1]*K[22]/K[7]+K[94]+K[24])
1150 K[97]=K[98]/K[7]*2
1160 K[83]=K[46]+2*K[29]+K[10]
1170 K[84]=K[14]*K[26]+(K[42]-K[85])*2-K[10]
1180 K[62]=K[61]*K[84]
1190 K[46]=K[17]*2+SQR((K[14]*K[26])^2+K[15]^2)
1200 K[53]=(K[14]*K[26]+K[42])*2
1210 K[59]=K[14]*K[26]+2*K[42]+K[100]
1220 K[60]=2*K[14]+K[43]
1230 K[71]=K[58]*K[59]*K[60]
1240 K[85]=K[29]*K[25]*K[1]
1250 K[71]=(K[14]*K[15]*2*(K[60]+K[42]))*K[26]
1260 K[72]=K[71]*K[9]
1270 K[73]=K[72]*K[13]
1280 K[56]=K[32]*K[7]*(K[61]^2-K[83]^2)*PI/4
1290 K[57]=K[33]*K[7]*(K[62]^2-K[83]^2)*PI/4
1300 K[93]=3.844E-03*K[32]*K[64]/PI
1310 K[68]=K[56]+K[57]
1320 K[53]=K[36]/K[1]
1330 K[75]=K[86]*K[53]*K[24]/2
1340 K[74]=K[73]+K[68]+K[75]
1350 K[49]=K[36]/(K[36]+K[74])
1360 K[99]=K[53]*K[12]
1370 K[81]=K[33]*PI*(K[62]^2-K[83]^2)*(K[34]/K[99])^2/4
1380 K[67]=K[81]*K[7]/K[34]
1390 K[45]=(K[98]+K[67]*K[99])/K[82]
1400 K[47]=K[45]*K[34]/K[7]
1410 K[65]=(K[62]-K[83])*PI/2
1420 K[41]=SQR(4*K[3]*K[65]*K[45]/PI/K[67])
1430 K[31]=INT(LOG(K[41]/0.32474)/(-0.11592))
1440 K[41]=0.32474/EXP(K[31]*0.11592)
1450 K[39]=0.05
1470 D=K[83]+2*K[47]*(K[41]+2*K[21])^2/(K[39]-K[21])
1480 IF D<K[84] THEN 1510
1490 K[62]=0.9*K[62]
1500 GOTO 1280

```

Figure 23. Modified Design Program - 200 KVA T/R Unit No. 2.

```

1510 IF ABS(D-K[62])/D<0.01 THEN 1540
1520 K[62]=(D+K[62])/2
1530 GOTO 1280
1540 K[92]=3.044E-03*K[33]*K[65]/PI
1550 K[88]=K[38]-2*K[39]-K[92]-K[87]-2*K[91]-K[93]
1560 K[92]=K[92]+K[88]*(K[88]>0)
1570 K[54]=K[36]/K[49]
1580 K[55]=K[12]*K[54]/K[2]
1590 K[66]=K[56]/K[55]+2
1600 K[80]=K[66]*K[35]+2/K[7]
1610 K[44]=(K[2]-K[66]*K[55])/K[82]
1620 K[16]=K[44]/K[7]*K[35]
1630 K[64]=(K[61]-K[83])*PI/2
1640 K[40]=SQRT(4*K[3]+K[64]*K[16]/PI/K[66]*K[7]/K[35]+2)
1650 K[30]=INT(LOG(K[40]/0.32474)/(-0.11592))
1660 K[40]=0.32474/EXP(K[30]*0.11592)
1670 K[91]=0.039
1680 D=K[83]+2*K[16]*(K[40]+K[18])+2/(K[91]-K[18])
1700 IF D<K[84] THEN 1730
1710 K[61]=0.9*K[61]
1720 GOTO 1280
1730 IF ABS(D-K[61])/D<0.01 THEN 1760
1740 K[61]=(D+K[61])/2
1750 GOTO 1280
1760 IF K[52]<K[92] THEN 1780
1770 K[92]=K[52]
1780 IF K[27]<K[93] THEN 1800
1790 K[93]=K[27]
1810 K[63]=K[7]*(K[39]+K[91]+(K[92]+K[93])/2+K[87])+K[27]
1820 IF K[43]<K[63] THEN 1860
1850 GOTO 1850
1860 K[43]=1.5*K[43]
1870 GOTO 1190
1880 K[69]=(K[64]+K[16]*K[7]*K[40]+2*K[65]*K[45]+K[41]+2)*PI/4
1890 K[70]=K[69]*K[8]
1900 K[78]=K[77]-K[71]-K[69]-K[14]+K[59]+K[60]
1910 K[79]=K[78]*0.0565
1920 K[50]=K[79]+K[70]+K[72]+K[86]-K[37]/16
1930 K[95]=K[50]/K[36]*1000
1940 K[96]=K[45]/K[44]
1950 K[51]=1-K[98]+K[44]/K[2]/K[45]
1960 K[43]=INT(K[40]*8+1)/8
1970 K[60]=K[43]+2*K[14]
1980 K[20]=(K[43]-K[63])/2
1990 D=K[62]*(K[62]<K[61]+K[61]*(K[61]<=K[62]))
2000 K[76]=K[7]*PI+3.19E-08*K[16]+2*(D+K[83])/(D-K[83])

```

Figure 23 (Cont'd.). Modified Design Program - 200 KVA T/R Unit 2.

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```

2010 K[76]=(K[76]+(K[87]+(K[39]+K[91])/3)/K[35])^2
2020 K[89]=(D+2-K[83])^2*K[7]*4.5*1.77E-13/K[87]
2030 K[48]=INT(K[39]/K[41])
2040 K[90]=INT(K[91]/K[40])
2050 DISP "1=STORE;2=LIST;3=PLOT":
2060 INPUT X
2070 GOTO X OF 2090,2140,2150
2080 GOTO 2050
2090 DISP "DATA FILE #":
2100 INPUT F
2110 K[120]=F
2120 STORE DATA F
2130 GOTO 2050
2140 LINK 2,1000,1000
2150 LINK 4,1000,1070
2160 END

```

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Figure 23 (Cont'd.). Modified Design Program - 200 KVA T/R Unit 2.

1	DC OUTPUT VOLTAGE---	2.5000E+04	51	REGULATION-----	5.5510E-03
2	INPUT VOLTAGE-----	5.7000E+02	52	COOLING SPACE, SEC---	3.0000E-02
3	WIRE RESISTIVITY----	7.4300E-07	53	DC OUTPUT CURRENT--	8.0000E+00
4	CORE STACKING FACTOR	8.5000E-01	54	INPUT POWER-----	2.0251E+05
5	FLUX DENSITY-----	5.0000E+04	55	INPUT CURRENT-----	4.9028E+02
6	FREQUENCY-----	1.0000E+04	56	PRIMARY LOSS-----	7.7594E+02
7	NO. PIES-----	3.2000E+01	57	SECONDARY LOSS-----	7.8095E+02
8	WIRE DENSITY-----	3.2400E-01	58	HEIGHT-----	5.0000E+00
9	CORE DENSITY-----	3.0200E-01	59	WIDTH-----	5.0000E+00
10	RADIAL ADJUST-----	0.0000E+00	60	LENGTH-----	6.5000E+00
11	VOLTAGE FORM FACTOR--	1.0000E+00	61	PRI. O.D.-----	3.0502E+00
12	CURRENT FORM FACTOR--	1.3800E+00	62	SEC. O.D.-----	3.1318E+00
13	CORE DISS. RATE-----	8.0000E+01	63	WINDING HEIGHT-----	4.5530E+00
14	CORE LEG WIDTH-----	5.0000E-01	64	PRI. MEAN LENGTH----	1.5881E+00
15	CORE LEG DEPTH-----	1.0000E+00	65	SEC. MEAN LENGTH----	1.7162E+00
16	PRI. TURNS PER PIE--	1.6718E+01	66	PRI. RES.-----	3.2201E-03
17	SPOOL THICKNESS-----	6.2500E-02	67	SEC. RES.-----	6.4074E+00
18	PRI. INSUL SPACE----	1.3000E-03	68	COPPER LOSS-----	1.5569E+03
19	WINDOW LENGTH ADJ----	7.5000E-01	69	WINDING VOL.-----	1.4955E+00
20	PRI. SPACE OUTSIDE--	4.7350E-01	70	WINDING WEIGHT-----	4.8454E-01
21	SEC. INSUL SPACE----	1.7000E-03	71	CORE VOL.-----	1.6000E+01
22	RECTIFIER FACTOR----	1.0100E+00	72	CORE WEIGHT-----	4.8320E+00
23	RECTIFIER PRV-----	1.0000E+03	73	CORE LOSS-----	3.8656E+02
24	RECT. FWD. VOLT DROP	1.1000E+00	74	TOT. PWR. LOSS-----	2.5066E+03
25	BREAKDOWN FACTOR-----	1.0000E-05	75	RECTIFIER LOSSES----	5.6320E+02
26	CORE FORM FACTOR----	2.0000E+00	76	LEAKAGE INDUCTANCE--	9.6350E-07
27	COOLING SPACE, PRIM--	2.5000E-02	77	TANK VOL.-----	1.6250E+02
28	RECT SAFETY FACTOR--	1.2000E+00	78	COOLANT VOL.-----	1.2875E+02
29	SEC INNER KEEPBACK--	2.5000E-01	79	COOLANT WEIGHT-----	7.2746E+00
30	PRI. WIRE GAUGE-----	2.0000E+01	80	RES. SINGLE PRI. PIE	2.5824E-02
31	SEC. WIRE GAUGE-----	2.4000E+01	81	RES. SINGLE SEC. PIE	2.0023E-31
32	PRI. HEAT TRANS.-----	6.0000E+00	82	VOLTS PER TURN-----	1.7000E+01
33	SEC. HEAT TRANS.-----	5.5000E+00	83	PIE I.D.-----	2.0392E+00
34	NO. PARALLEL SECS.--	1.0000E+00	84	PIE O.D.-----	3.5000E+00
35	NO. PARALLEL PRIS.--	1.6000E+01	85	SEC OUTER KEEPBACK--	2.5000E-01
36	MAX PWR. OUTPUT-----	2.0000E+05	86	TOTAL NO. RECTIFIERS	1.2800E+02
37	RECTIFIER WGT. , OZ--	4.0000E-02	87	PRI-SEC SPACER-----	2.5000E-02
38	RECTIFIER THICKNESS--	2.1000E-01	88	SEPARATION ADJUST----	1.1650E-02
39	THICKNESS SEC. PIE--	5.0000E-02	89	CAPACITANCE-----	5.2460E-09
40	PRI. WIRE DIA.-----	3.1964E-02	90	# LAYERS, PRIMARY----	1.0000E+00
41	SEC. WIRE DIA.-----	2.0105E-02	91	THICKNESS PRI. PIE--	3.9000E-02
42	WINDOW WIDTH-----	1.5000E+00	92	SECONDARY SEPARATION	3.0000E-02
43	WINDOW HEIGHT-----	5.5000E+00	93	PRIMARY SEPARATION--	2.5000E-02
44	PRI. TURNS PER//PATH-	3.3436E+01	94	NO. RECTS. PER LEG--	2.0000E+00
45	SEC. TURNS-----	1.4936E+03	95	SPECIFIC WEIGHT-----	6.4556E-02
46	SPOOL O.D.-----	1.5392E+00	96	TURNS RATIO-----	4.4670E+01
47	SEC. TURNS PER PIE--	4.6675E+01	97	BRIDGE INPUT VOLTAGE	1.5825E+03
48	# LAYERS, SEC.-----	2.0000E+00	98	AC OUTPUT VOLTAGE---	2.5320E+04
49	EFFICIENCY-----	9.8762E-01	99	AC OUTPUT CURRENT---	1.1040E+01
50	TOT. WEIGHT-----	1.2911E+01	100	WIDTH ADJUST-----	1.0000E+00

Figure 24. Design Parameters - Modified Program

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### 3.3.4 200 KW T/R Unit Heat Transfer System Design

Heat transfer from the heat source in the 200 KW T/R Unit occurred primarily through three paths in series:

- (a) Heat transfer from the sources into the coolant (F113) by nucleate boiling at the source surface.
- (b) Heat transfer from the coolant vapor to the lower finned surface of the cover by condensation, with gravity liquid (condensate) return.
- (c) Heat transfer from the cover (condenser) to the water coolant.

Other heat transfer paths (sides, ends & bottom of container) to the environment were assumed negligible.

At final assembly, all air was purged from the transformer system, resulting in only F113 (liquid or vapor) being present within the case. Since the case was of fixed internal volume, the internal pressure varied as a function of the F113 temperature. Any component heated above the temperature of the surrounding F113 liquid produced local boiling since the internal pressure was the vapor pressure of the bulk liquid.

Three heat source types were evaluated with reference to their temperature rise above the bulk F113 liquid: (a) primary and secondary pie windings, (b) diodes, and (c) core.

#### 3.3.4.1 Pie Windings

The heat dissipated in the primary and secondary windings was given by the transformer design program (K32 and K33) as 29.5 and 23 watts/sq.in respectively. In a liquid, such as F113 the temperature rise may be determined by:

$$t = 5.2 q^{0.293} \text{ C} \quad (4a)$$

or

$$t = 9.36 q^{0.293} \text{ F} \quad (4b)$$

where  $t$  = surface temperature rise  
 $q$  = heat transfer rate, watts/sq.in.

For the primary and secondary pie windings, this results in surface temperature rises of 14.0 and 13.0°C respectively.

#### 3.3.4.2 Diodes

The heat is generated at the diode junctions and transferred primarily through the leads. The average loss per diode is 4.4 watts, or 2.2 watts per lead. The leads are .375 inch long (neglecting terminals), and 0.05 inch diameter, having a surface area of 0.059 sq.in., an average heat transfer rate of 37.35 watts/sq in, and an average temperature rise of 15°C. However, because of the high surface heat transfer rate the effectiveness of the lead in transferring heat to the Freon is estimated to be about 70% because of the axial temperature gradient, and the temperature rise at the base of the lead with respect to the bulk fluid temperature is estimated to be 21.4°C. The internal resistance of the diode is assumed at 15 C/watt. The internal temperature rise is  $15 \times 2.2 = 33^\circ\text{C}$ . Thus, the junction temperature rise with respect to the bulk F113 temperature is 54.4°C. Since the Freon boils at 47°C(1), the junction temperature is 101.4°C.

#### 3.3.4.3 Core

The core dissipative area is approximately 32 square inches (side surfaces only). The surface heat transfer rate is  $380.96/32 = 11.91$  watts/sq.in. The core surface temperature rise at this rate is 10.7°C; the core surface temperature is 57.7°C.

#### 3.3.4.4 Condensation Process

The lower surface of the top cover is vertically finned to provide condensation surfaces for the F113 vapor. The heat transfer coefficient for condensation is given by

$$h = 0.943 \left[ \frac{\rho_L^2 g k^3 \lambda}{\mu_L L F} \right]^{1/4} \quad (5)$$

(1) DuPont Bulletin E-11, pg 9.

where

- $h$  = heat transfer coefficient BTUH/(sq ft-F)
- $\rho_L$  = liquid density (93.1 for F113), lbs/cu.ft.
- $g$  = 4.17E8 ft/hr<sup>2</sup>
- $k$  = fluid conductivity (0.0335), BTUH/(ft.F)
- $\lambda$  = latent heat of vaporization (63.12)BTU/lb.
- $\mu_L$  = liquid viscosity (1.14), lb/(ft.hr)
- $L$  = fin length, ft.
- $F$  = temperature difference, fin-to-condensate deg.F.

Substituting the values for F113

$$h = 277.73 \left( \frac{1}{LF} \right)^{1/4}$$

This value must be modified by appropriate factors for fin effectiveness.

The effectiveness  $n$ , is defined as

$$n = \tanh (aL)/aL$$

where

- $\tanh (aL)$  = hyperbolic tangent  $aL$
- $a = \sqrt{2 h/k_F t}$
- $k_F$  = fin thermal conductivity BTUH/(sq.ft-F)ft)
- $t$  = fin thickness, ft.

The overall heat transfer equation is defined by

$$Q = h n S F$$

where

- $Q$  = heat transfer rate, BTUH(= 3.413 watts)
- $S$  = condensation surface area, sq ft.

Numerous combinations of fin thickness and fin spacing were evaluated for the temperature difference,  $F$ , when transferring 8,500 BTUH (2490 watts). In general,  $F$  is minimized by small fin thickness and spacings, since these provide greater surface area,  $S$ , for a given plan area. For ease of fabrication, and

to prevent condensate bridging between fins, fin thickness and spacing were set at 1/16 inch. The attached curve (Fig.25), shows the effect on F of varying fin length, L. Fin length was set at 3/8 inch, yielding a temperature difference of approximately 21F (11.7C).

#### 3.3.4.5 Water cooled cover

The condenser fins and cover are cooled by water flowing through passages drilled in the cover. Various passage sizes and series/parallel passage arrangements were evaluated to determine a suitable combination of temperature rise and pressure drop. The configuration finally elected consists of six 1/4 inch cooling passages in parallel, each 5 inches long, served by a 3/8 inch diameter inlet and outlet headers. Figure 26 shows the temperature difference and pressure drop of this arrangement, as a function of flow rate. It is recommended that approximately 4-5 GPM of water be maintained in the system, although satisfactory results can be obtained with as little as 1 GPM, 75 F inlet water.

#### 3.3.4.6 Temperature Limitations

Transformer pies: Limited by wire insulation :	356F(180 C)
Core	212F(100 C)
Diode junctions	302F(150 C)
F113 (limited to 20PSIG internal pressure)	170F( 77 C)

#### 3.3.4.7 Temperature rise summary

Primary pie to F113	14.0C
Secondary pie - to - F113	13.0C
Core - to - F113	10.7C
Diode Junction - to F113	54.4C
Condensate (F113) - to - cover	11.7C
Cover - to - water	Function of GPM

Figure 25

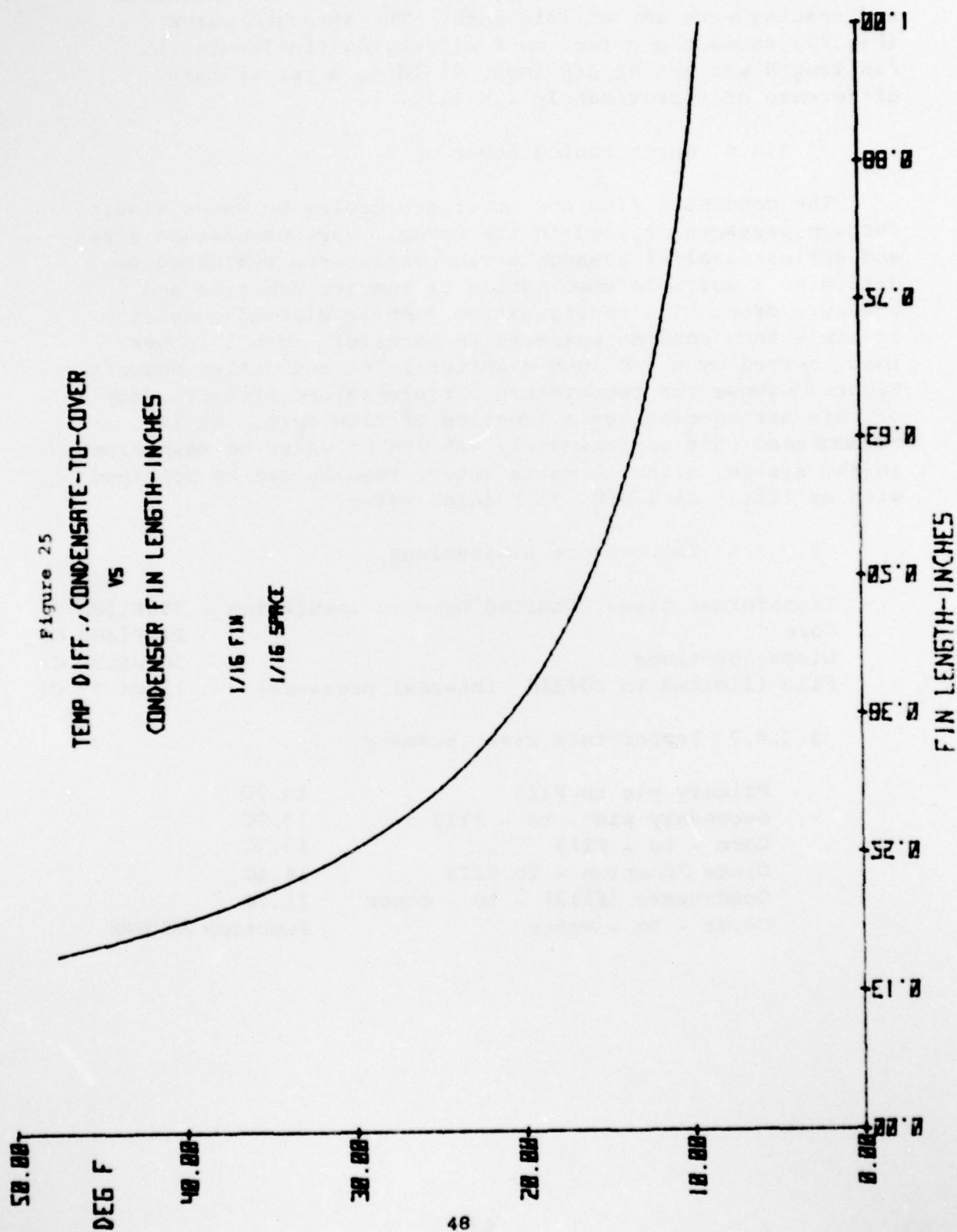
TEMP DIFF., CONDENSATE-TO-COVER

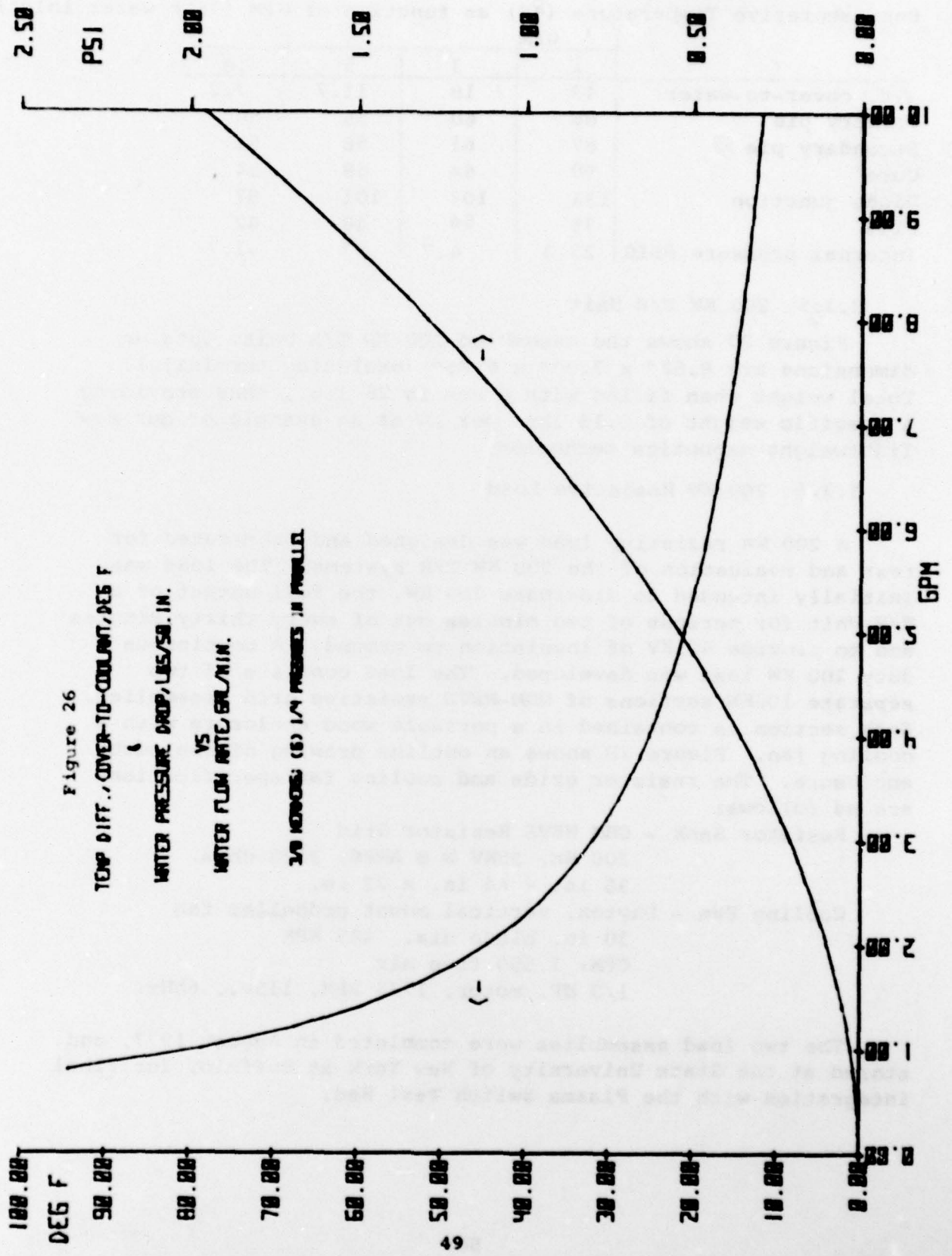
VS

CONDENSER FIN LENGTH-INCHES

1/16 FIN

1/16 SPACE





Representative Temperature ( $^{\circ}\text{C}$ ) as function of GPM (75 F water inlet)

	GPM			
	1	3	5	10
$\Delta t$ , cover-to-water	43	18	11.7	7.2
Primary pie	86	60	55	50
Secondary pie	87	61	56	51
Core	90	64	58	54
Diode junction	133	107	101	97
F113	79	54	48	42
Internal pressure, PSIG	23.3	4.7	0	-1.7

### 3.3.5 200 KW T/R Unit

Figure 27 shows the assembled 200 KW T/R Unit. Outside dimensions are 8.62" x 7.00" x 6.25" (excluding terminals). Total weight when filled with Freon is 26 lbs., thus providing a specific weight of 0.13 lbs. per KW as an example of our new lightweight magnetics technology.

### 3.3.6 200 KW Resistive Load

A 200 KW resistive load was designed and fabricated for test and evaluation of the 200 KW T/R systems. The load was initially intended to dissipate 200 KW, the full output of a T/R Unit for periods of two minutes out of every thirty minutes and to provide 40 KV of insulation to ground. A continuous duty 200 KW load was developed. The load consists of two separate 100KW sections of OHM-WEVE resistive grid assemblies. Each section is contained in a portable wood enclosure with a cooling fan. Figure 28 shows an outline drawing of one such enclosure. The resistor grids and cooling fan specifications are as follows:

Resistor Bank - OHM WEVE Resistor Grid

200 KW, 25KV @ 8 AMPS, 3125 ohms.

35 in. x 44 in. x 22 in.

Cooling Fan - Dayton, vertical mount propeller fan

30 in. blade dia., 485 RPM

CFM: 7,550 free air

1/3 HP. motor, 1725 RPM, 115V., 60Hz.

The two load assemblies were completed in August 1977, and stored at the State University of New York at Buffalo, for final integration with the Plasma Switch Test Bed.

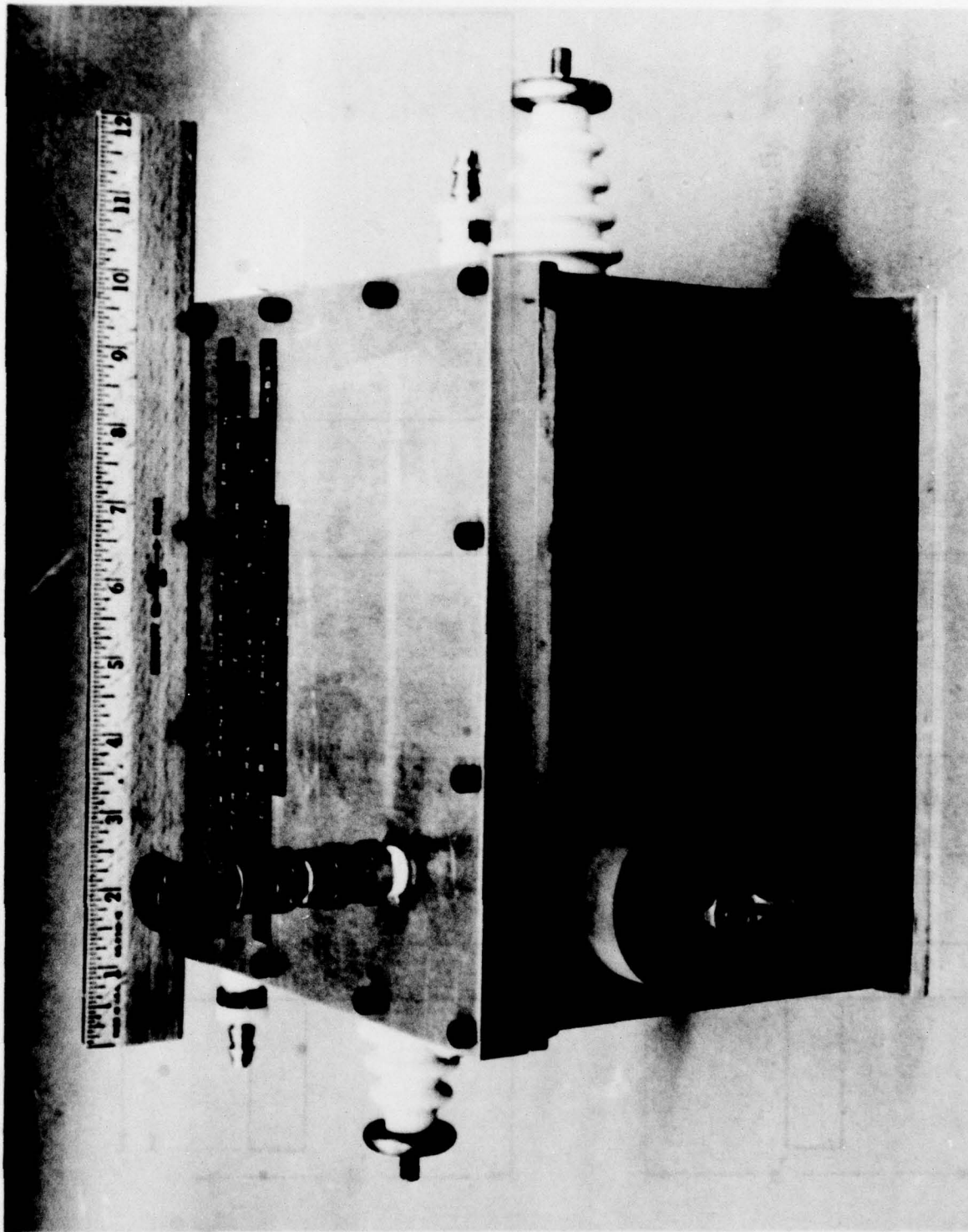
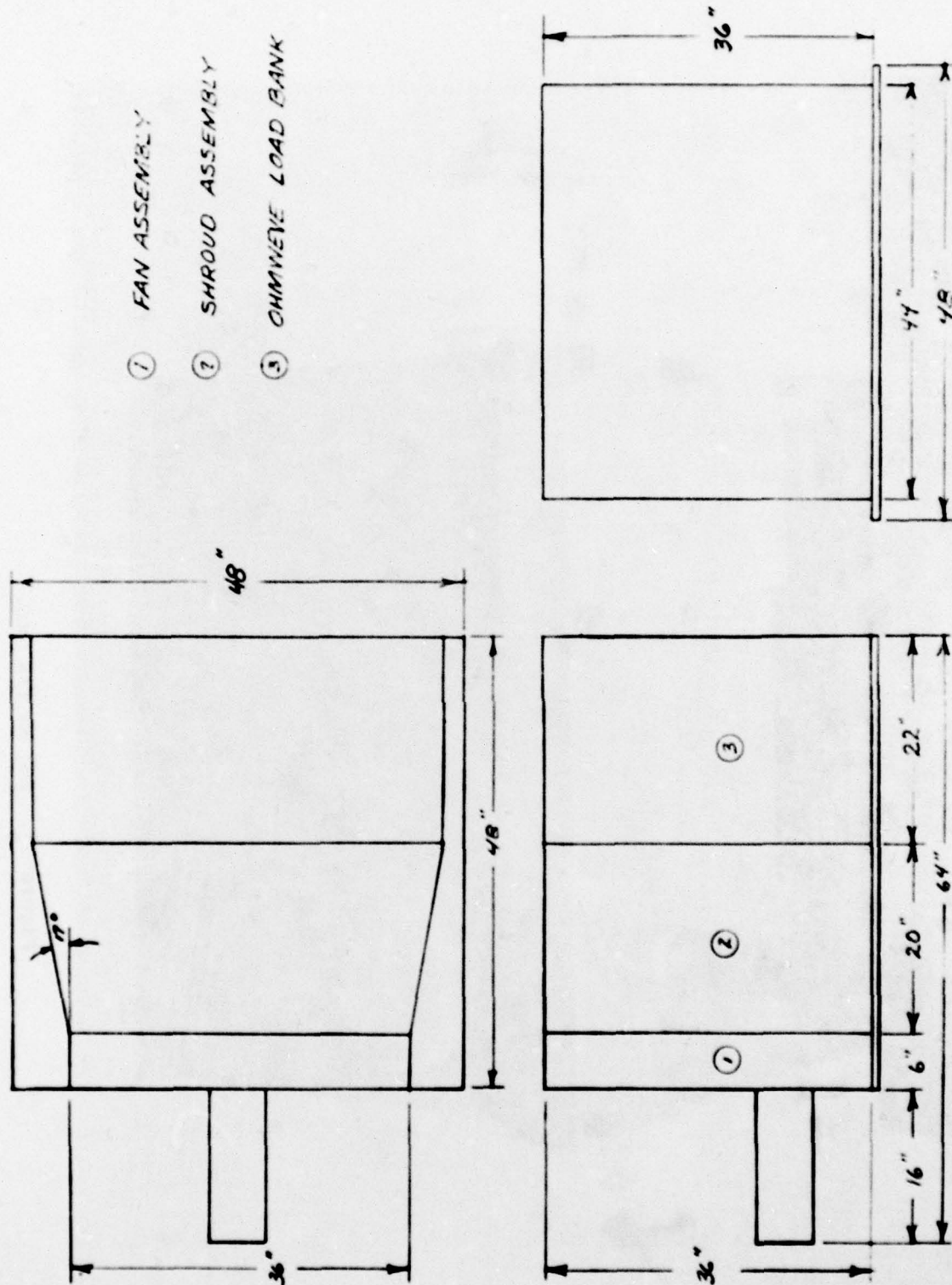


Figure 27. 200 KW T/R Unit



ONE HALF - 200KW. LOAD BANK SYSTEM

Figure 28

## SECTION IV

### CONCLUSIONS

All of the primary efforts of this program have been successfully accomplished:

- A 10 KVA inverter transformer was designed, fabricated and tested.
- Two 10 KVA transformer/rectifier (T/R) units (one liquid-cooled version and one air-cooled version) were fabricated and delivered.
- Research was conducted into the characteristics of magnetic and dielectric materials, improved magnetic circuit modeling, and application of advanced heat transfer techniques.
- Computer-aided design methods were utilized and specialized programs developed to permit extensive manipulation of multiple design parameters.
- An experimental 200 KVA inverter transformer was designed.
- Two 200 KVA T/R units were developed, fabricated, subjected to preliminary testing and delivered. (Full load testing awaits delivery of a 200 KW inverter. An addendum report will be issued after completion of the full load tests.)
- A high voltage non-inductive load suitable for testing the above T/R units was designed, fabricated, tested and delivered.

The overall intent of this program, to reduce the specific weight of inverter transformers without sacrifice of either electrical performance or reliability, has been realized. The goal of achieving a specific weight of 0.25 lb/KVA was exceeded. A specific weight of approximately 0.10 lb/KVA was actually accomplished with the deliverable 200 KVA transformers. Electrical performance was not sacrificed; the final design of the inverter transformers had unusually low leakage inductance and high efficiency. Reliability is expected to be considerably higher than conventional transformers because of the considerably reduced internal operating temperatures (ie; lower thermal stress) on conductors and insulation. In addition, the transformers can absorb severe overloads without damage, due to the capability of the vaporization cooling technique to safely dissipate large amounts of power.

The total measured specific weight of the complete 200 KVA T/R units (ie: rectifiers included) was about 0.13 lb/KVA. It is anticipated that in larger units, specific weights of the order of 0.07 lb/KVA can be realized. Also, production units can be made even lighter since lower weight case construction can be designed. The case design of the units delivered under this program was deliberately made heavier than necessary for experimental safety reasons.

Finally, a comment regarding the vaporization cooling fluid must be made. DuPont Freon 113 was used in this program primarily for convenience and economy. It is of relatively low cost, and was readily available. Freon 113 however, has a boiling temperature that is lower than what the Air Force may ultimately choose to use. Several varieties of coolants such as other Freons and fluorocarbons have been developed. They have higher boiling points than Freon 113 and have essentially identical thermal characteristics. These coolants will meet military specifications without the need for high pressure case designs.

APPENDIX A  
NON-ITERATIVE TRANSFORMER  
DESIGN PROGRAM

```

1000 COM L$(160),K$(210)
1010 DIM A$(40)
1020 PRINT "PIE WOUND TRANSFORMER DESIGN RECTANGULAR PRIMARY"
1030 DISP "LOAD DATA FILE #";
1040 INPUT F
1050 LOAD DATA F
1060 GOSUB 1050
1065 DISP "FOR SAME HEADING CONT. 1090"
1066 STOP
1070 DISP "ENTER FIRST HEADING";
1080 INPUT L$(1,80)
1090 PRINT TAB99
1100 DISP "CHANGE K VALUES & CONTINUE!"
1110 STOP
1120 K(82)=4.44E-08*K(6)*K(14)*K(26)*K(15)*K(4)*K(5)
1130 K(46)=K(17)*2+SQR((K(14)*K(26))^2+K(15)^2)
1140 K(77)=(K(14)*K(26)+K(42))*2*(K(14)*K(26)+2*K(42))*(2*K(14)+K(43))
1150 K(85)=K(25)*K(1)
1160 K(71)=(K(14)*K(15)*2*(2*K(14)+K(42)+K(43)))*K(26)
1170 K(72)=K(71)*K(9)
1180 K(73)=K(72)*K(13)
1190 K(29)=K(85)/K(7)
1200 K(83)=K(46)+2*K(29)+K(48)
1210 K(84)=K(14)*K(26)+(K(42)-K(85))*2-K(90)
1220 K(38)=K(84)
1230 K(37)=K(83)
1240 K(27)=PI*(K(84)^2-K(83)^2)/4
1250 K(65)=K(64)=PI*(K(84)+K(83))/2
1260 K(59)=K(32)*K(27)
1270 K(58)=K(33)*K(27)
1280 K(91)=K(58)+K(59)
1290 K(92)=1.522E-03*K(91)*K(35)+K(88)
1300 K(57)=K(58)*K(7)
1310 K(56)=K(59)*K(7)
1320 K(68)=K(56)+K(57)
1330 K(100)=K(36)
1340 K(74)=K(73)+K(68)
1350 K(49)=K(100)/(K(100)+K(74))
1360 K(53)=K(100)/K(1)
1370 K(81)=K(33)*PI*(K(84)^2-K(83)^2)*(K(34)/K(53))^2/4
1380 K(67)=K(81)*K(7)/K(34)
1390 K(45)=(K(1)+K(67)*K(53))/K(82)
1400 K(47)=K(45)*K(34)/K(7)
1410 K(41)=SQR(4*K(3)*K(65)*K(45)/PI/K(67))
1420 K(31)=INT(LOG(K(41)/0.32474)/(-0.11592))
1430 K(39)=2*K(47)*(K(41)+K(21))^2/(K(84)-K(83))+K(21)
1440 IF K(39)>(K(41)+2*K(18)) THEN 1460
1450 K(39)=(K(41)+2*K(18))

```

```

1460 K[62]=K[7]*K[39]
1470 K[54]=K[100]/K[49]
1480 K[55]=K[54]/K[2]
1490 K[66]=K[56]/K[55]^2
1500 K[80]=K[66]*K[35]/K[7]
1510 K[44]=(K[2]-K[66]*K[55])/K[82]
1520 K[16]=K[44]/K[7]*K[35]
1530 K[30]=(K[84]-K[83])/K[16]-2*K[18]
1540 K[40]=K[3]*K[64]*K[7]/K[35]/K[66]/K[30]
1550 K[61]=K[7]*(K[40]+2*K[19])
1560 IF K[52]<K[92] THEN 1580
1570 K[92]=K[52]+K[88]
1580 IF K[92]>K[85]/K[7] THEN 1600
1590 K[92]=K[85]/K[7]+K[88]
1600 K[63]=K[61]+K[62]+K[7]*(K[92]+K[87])+2*K[20]-K[92]
1610 IF K[43]>K[63] THEN 1650
1620 K[100]=K[100]-K[28]
1630 IF K[100]<K[28] THEN 2480
1640 GOTO 1350
1650 K[69]=(K[64]*K[44]*K[40]^2+K[65]*K[45]*K[41]^2)*PI/4
1660 K[70]=K[69]*K[8]
1670 K[78]=K[77]-K[71]-K[69]
1680 K[79]=K[78]*K[10]
1690 K[50]=K[79]+K[70]+K[72]
1700 K[95]=K[50]/K[100]*1000
1710 K[96]=K[45]/K[44]
1720 K[51]=1-K[1]*K[44]/K[2]/K[45]
1730 GOSUB 1860
1740 DISP "STORE DATA FILE #";
1750 INPUT F
1760 PRINT TAB50
1770 IF F=0 THEN 1090
1780 IF F<21 THEN 1740
1790 STORE DATA F
1800 GOSUB 1840
1810 DISP "FOR PLOT CONT 2520"
1820 STOP
1830 GOTO 1090
1840 PRINT "TRANSFORMER DESIGN DATA"
1850 PRINT TAB73"DATA FILE #",F,TAB99
1860 RESTORE 1960
1870 WRITE (15,1890)L$(1,80)
1880 PRINT TAB73
1890 FORMAT /,F2.0
1900 FOR I=1 TO 50
1910 READ A$
1920 WRITE (15,1940)I,A$(1,20),K[I],I+50,A$(21,40),K[I+50]
1930 NEXT I
1940 FORMAT F3.0,1X,E12.4,F6.0,1X,E12.4
1950 RETURN
1960 DATA "OUTPUT VOLTAGE-----REGULATION-----"
1970 DATA "INPUT VOLTAGE-----MIN COOLING SPACE----"

```

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1980 DATA "WIRE RESISTIVITY----OUTPUT CURRENT-----"
1990 DATA "CORE STACKING FACTORINPUT POWER-----"
2000 DATA "FLUX DENSITY-----INPUT CURRENT-----"
2010 DATA "FREQUENCY-----PRIMARY LOSS-----"
2020 DATA "NO. PIES-----SECONDARY LOSS-----"
2030 DATA "WIRE DENSITY-----SEC LOSS PER PIE-----"
2040 DATA "CORE DENSITY-----PRI LOSS PER PIE-----"
2050 DATA "COOLANT DENSITY-----"
2060 DATA "-----PRI. HEIGHT-----"
2070 DATA "-----SEC. HEIGHT-----"
2080 DATA "CORE DISS. RATE-----WINDING HEIGHT-----"
2090 DATA "CORE LEG WIDTH-----PRI. MEAN LENGTH-----"
2100 DATA "CORE LEG DEPTH-----SEC. MEAN LENGTH-----"
2110 DATA "PRI. TURNS PER PIE--PRI. RES.-----"
2120 DATA "SPOOL THICKNESS-----SEC. RES.-----"
2130 DATA "PRI. TURN SPACE-----COPPER LOSS-----"
2140 DATA "PRI. PIE SPACE-----WINDING VOL.-----"
2150 DATA "PRI. SPACE OUTSIDE--WINDING WEIGHT-----"
2160 DATA "SEC. TURN SPACE-----CORE VOL.-----"
2170 DATA "-----CORE WEIGHT-----"
2180 DATA "-----CORE LOSS-----"
2190 DATA "-----TOT. PWR. LOSS-----"
2200 DATA "BREAKDOWN FACTOR-----"
2210 DATA "CORE FORM FACTOR-----"
2220 DATA "COIL SURFACE AREA---TANK VOL.-----"
2230 DATA "PWR. INCR.-----COOLANT VOL.-----"
2240 DATA "SEC INNER KEEPBACK--COOLANT WEIGHT-----"
2250 DATA "PRI. WIDTH-----RES. SINGLE PRI. PIE"
2260 DATA "SEC. WIRE GAUGE-----RES. SINGLE SEC. PIE"
2270 DATA "MAX PRI. HEAT TRANS.VOLTS PER TURN-----"
2280 DATA "MAX SEC. HEAT TRANS.SEC. PIE I.D.-----"
2290 DATA "NO. PARALLEL SECS.--SEC-PIE O.D.-----"
2300 DATA "NO. PARALLEL PRIS.--SEC OUTER KEEPBACK--"
2310 DATA "MAX PWR. OUTPUT-----"
2320 DATA "PRI. I.D.-----PRI-SEC SPACER-----"
2330 DATA "PRI. O.D.-----SEPARATION ADJUST-----"
2340 DATA "THICKNESS SEC. PIE--CORE IDENTIFICATION--"
2350 DATA "PRI. THICKNESS-----SEC O.D. ADJUST-----"
2360 DATA "SEC. WIRE DIA.-----TOT. HEATING RATE-----"
2370 DATA "WINDOW WIDTH-----ASSEMBLY SEPARATION--"
2380 DATA "WINDOW HEIGHT-----"
2390 DATA "PRI. TURNS-----"
2400 DATA "SEC. TURNS-----SPECIFIC WEIGHT-----"
2410 DATA "SPOOL O.D.-----TURNS RATIO-----"
2420 DATA "SEC. TURNS PER PIE-----"
2430 DATA "SEC I.D. ADJUST-----"
2440 DATA "EFFICIENCY-----"
2450 DATA "TOT. WEIGHT-----PWR. OUTPUT-----"
2460 PRINT TAB99
2470 END
2480 PRINT "INCONSISTENT PARAMETERS"
2490 GOSUB 1860
2500 GOTO 1090
2510 END
2520 IF K(26)=2 THEN 2540
2530 LINK 12,1000,1080
2540 LINK 0,1000,1090
2550 END

```

## APPENDIX B

### HP 9830 COMPUTER PROGRAMS

There are a total of six computer programs which were utilized for the design and development of the 200 KW transformers. These programs are identified by track No., as follows:

Track #0 - Single point design program

This program computes a transformer design for a given set of input parameters, both fixed and variable.

Track #1 - Design Program, Single variable ranging.

This program is similar to track 0, except that it generates a series of designs by allowing any one of the input variables to be varied through a specified range.

Track #2 - Output Listing

This program is linked by the design programs to provide an output listing. It would normally be a part of the design programs, but has been placed on a separate track because of machine memory limitations.

Track #3 - Design program, Multiple variable ranging.

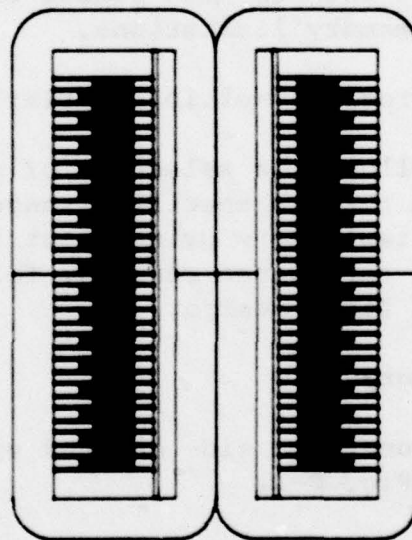
This program allows the selection of up to 5 variables which may be varied through specified ranges. Up to 5 selected output variables are printed out for each design. It is normally used for coarse ranging, followed by use of track 0 or 1 for finer design.

Track #4 - Plot program

This program generates side and end views of the transformer, as in Fig. B-1.

Track #5 - Plot program, Top view.

This program generates a top view of the transformer as in Fig. B-2.



200 KW INV TRANSF

TAPE#5, FILE# 11

SCALE 1/2 ; 7 X 10

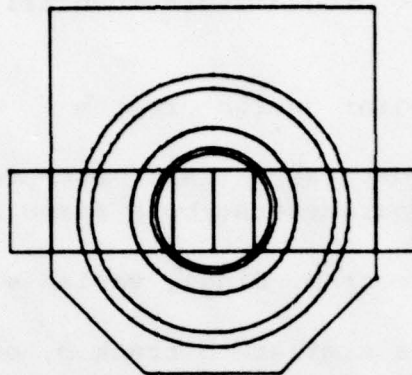
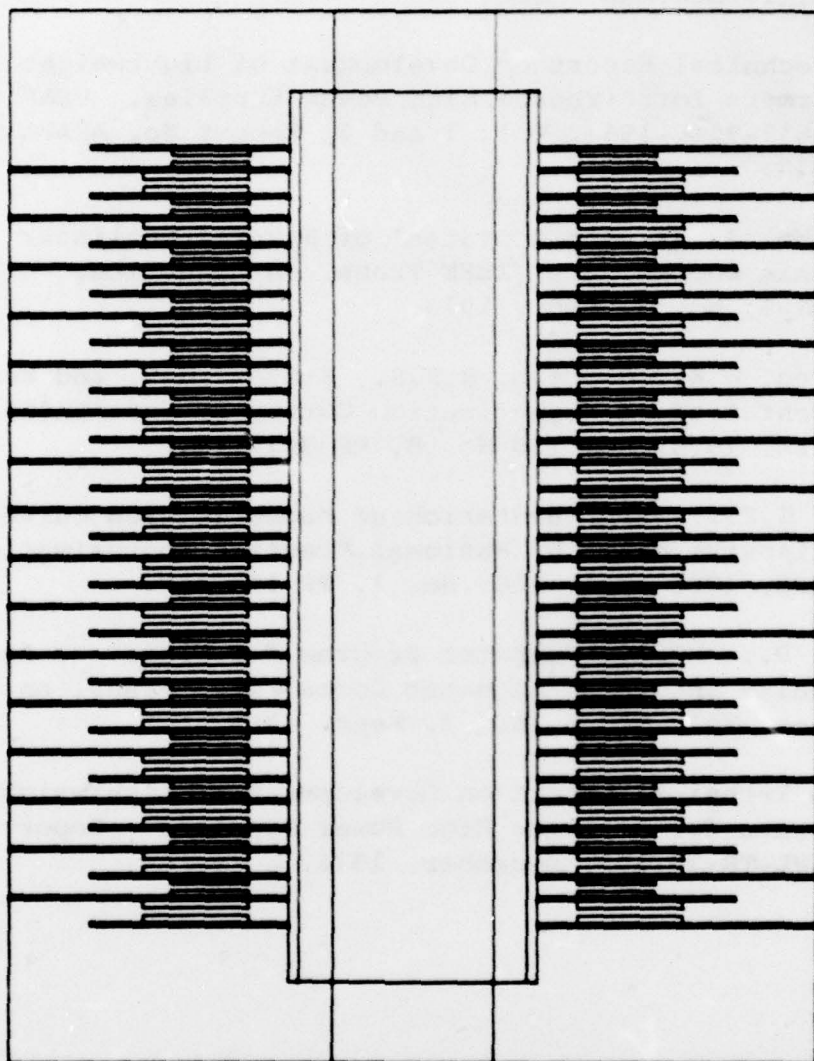


Figure B-1. Computer Generated Plot (Side and End Views)



200 KW INV TRANS      TAPE#5, FILE# 11  
 TDP VIEW      SCALE 1 / 1 ; 7 X 10

Figure B-2. Computer Generated Plot (Top View)

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